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Experimental Measurements of Longitudinal Load Distributions on Friction Stir Weld Pin Tools

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EXPERIMENTAL MEASUREMENTS OF LONGITUDINAL LOAD DISTRIBUTIONS ON FRICTION STIR WELD PIN TOOLS

by

Aaron L. Stahl

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

Department of Mechanical Engineering
Brigham Young University
December 2005
This thesis has been read by each member of the following graduate committee and by majority vote has been found to be satisfactory.

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Date ____________________________  Tracy W. Nelson

Date ____________________________  Michael P. Miles
As chair of the candidate’s graduate committee, I have read the thesis of Aaron L. Stahl in its final form and have found that (1) its format, citations, and bibliographical style are consistent and acceptable and fulfill university and department style requirements; (2) its illustrative materials including figures, tables, and charts are in place; and (3) the final manuscript is satisfactory to the graduate committee and is ready for submission to the university library.

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Accepted for the Department

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Graduate Coordinator

Accepted for the College

Alan R. Parkinson
Dean, Ira A. Fulton College of Engineering and Technology
The longitudinal forces generated from the Friction Stir Welding process are substantial. An understanding of these forces is critical to proper tool design. This study describes a technique to measure the longitudinal force distribution on a friction stir weld pin tool. Total longitudinal forces were recorded on a dynamometer while welding 6061 aluminum with non-threaded pins that varied in length and diameter. A model was developed that characterizes pin force as a function of pin length and diameter. Results suggest that force generally increases with pin length, while forces remain relatively constant with pin diameter. Unexpected force variation was found at large pin lengths, which yielded several possible models of the force distribution.
All of the modeled force distributions proved to be non-uniform and increase linearly with pin length, which produces a pin force that increases with the square of the pin length.
ACKNOWLEDGEMENTS

I wish to thank all those who contributed to the completion of this thesis. To the committee, for the work they provide to develop this technology and for allowing me to be a part of it. To Dr. Carl Sorensen, who offered numerous hours of assistance and most of all, patience. I would also like to thank my wonderful family and friends who have offered much love and support throughout this endeavor.
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CHAPTER 1: INTRODUCTION

This thesis is an experimental study that measures the longitudinal force distribution on a friction stir weld pin tool while welding 6061 aluminum. Forces were recorded on a dynamometer while welding with numerous tools with pins that varied in length and diameter. Force distributions were then generated from the force measurements. Some contributions of this research are to characterize longitudinal forces for various pin geometries and an understanding of how these forces are distributed along FSW pin tools. These contributions may aid in tool development for reducing energy requirements, and increasing process speeds and tool life.

1.1 Friction Stir Welding

Friction Stir Welding (FSW) was invented and patented by The Welding Institute (TWI) in 1991 [1]. The FSW process involves forcing a rotating tool consisting of a protruding pin and larger shoulder into a material, and traversing the tool along the workpiece joint. The rotating tool generates frictional heat which causes the material to plastically flow around the tool. The shoulder usually contains a concavity which allows material to flow and produces a forging pressure on the trailing end of the weld. See Figure 1 for a schematic view of the FSW process.
Unlike traditional arc welding processes, FSW is a solid-state joining process. Quality welds are typically produced at approximately 80% of the base material’s melting temperature. Therefore, FSW welds don’t suffer from solidification defects such as cracking and porosity as do traditional fusion welds. [2]

Inherent to the FSW process are the significant loads exerted by the pin tool on the workpiece. Understanding these forces and their implications on the pin is essential to proper tool development.
CHAPTER 2: EXPERIMENTAL MEASUREMENTS

2.1 Objective

This paper examines a method to experimentally measure the longitudinal force distribution on a friction stir weld pin tool while welding 6061-T6 aluminum. A proper understanding of the force distribution on the tool pin while welding, allows stresses to be analyzed and tool designs modified to minimize cracks and fractures and maximize tool longevity.

2.2 Background

2.2.1 Forces and Tool Geometry

There is a general agreement for the need to minimize FSW forces to reduce the energy required, increase process speeds and tool life. Recent work has shown that forces generated while welding are related to tool geometry. TWI [3] has measured the total lateral loads, thrust loads and torque for several tools that varied in shoulder diameter, pin diameter and pin length while welding various aluminums. The results showed that the use of a larger tool shoulder diameter caused higher welding torques, and that increasing the shoulder had a larger effect on torque than increasing the pin diameter. NASA [4] focused on characterizing axial forces by the pin independently of the shoulder, by varying the pin length with a Retractable Pin Tool. Correlations were made between
forces and the tool pin position in relation to the weld material backside. Data showed that the axial force increased when the distance from the pin to material backside decreased. Much work has also been performed on the relationship between tool forces and tool geometries and weld parameters. A study at Concurrent Technologies Corporation (CTC) examined the relationship between forces and certain tool features such as flats [5]. Testing found that travel per flat per revolution plays a role in determining transverse force.

2.2.2 Force Distributions

In addition to measuring the total forces experienced by a FSW pin tool, understanding how the force is distributed along the pin geometry is equally important. The examples in Figures 2 and 3 show possible force distributions along pin length and diameter. The three possible distributions along pin length in Figure 2 may be equal in total force, but each distribution will result in various degrees of shear and bending stress along the pin. These stresses will certainly be critical to the life of the tool. Knowing the force distribution along the pin can therefore be helpful in determining tool design characteristics, such as pin geometry and tool material. As far as could be determined by a literature search, this study is the first to explore the force distributions on a pin tool.
2.3.1 Method

To determine the force distribution on the tool in the longitudinal direction, a designed experiment was used. The experiment measured longitudinal forces on a dynamometer while friction stir welding with numerous tools that varied in geometry. Welds were made at several tool lengths with a constant pin diameter. Welds were then made at several pin diameters with a constant pin length. In all cases, tool tilt, shoulder diameter and shoulder angle were held constant. Forces were then used to obtain a force
distribution along the profile of the pin tool. Figures 2 and 3 are examples of possible distributions along pin length and diameter.

In order to examine a potential source of variation that occurred in the force data, an experiment was performed to determine force as a function of shoulder depth. To obtain this, a number of welds were run with one tool at various depths. Forces were then graphed against shoulder depth.

2.3.2 Equipment

Testing for this research occurred on a MegaStir FSW machine. Mounted to the machine table is a dynamometer which is capable of measuring up to 10 tons in the axial direction and 5 tons in the longitudinal direction. The resolution of the dynamometer in all directions is 1 pound. The machine also includes a computer with data acquisition capability.

2.3.3 Materials

Welds were processed on 12 in. wide by 24 in. long, 3/8 or 1/2 in. 6061-T6 aluminum-alloy plate. For tools with pin lengths up to 0.250 in, 3/8 in. thick aluminum plates were used. For tools with pin lengths longer than 0.250 in, 1/2 in. thick plates were used, as to avoid any pin interaction with the anvil. The tools were made from heat treated H13 tool steel. The pins were a smooth cylinder, containing no flats, threads, tapers or other welding enhancement designs, as shown in Figure 4. For all tools, the shoulder was kept
constant at 1 inch in diameter and an 8° concave cavity. Figure 5 is a drawing of a typical tool.

![Figure 4 Several tools used that vary in pin length](image1)

![Figure 5 Drawing of a tool with a 0.30 in. diameter and 0.25 in. length pin](image2)

For a pin diameter of 0.250 in, the pin length varied from 0.071 to 0.280 in. Pin lengths were separated by approximately 0.030 in. between 0.071 and 0.219 in. Between 0.219 and 0.280 in, pin lengths were separated by 0.015 in. For a pin length of 0.250 in, the diameter varied from 0.206 to 0.300 in. Also, tools with a pin length of 0.150 in. were
made with diameters varying from 0.206 to 0.300. Pin diameters were separated by approximately 0.030 in. Figure 6 shows the tool pin geometries that were used.

![Figure 6 Tool pin sizes](image)

2.3.4 Welding Procedure and Conditions

The plates were mounted on the dynamometer during welding and measured longitudinal force, lateral force, and axial force. The machine head tilt was 3 degrees. The primary welding parameters were 650 RPM spindle speed and a feed rate of 8 inches per minute (IPM). A feed rate of 6 IPM was also explored with constant length tools that varied in pin diameter.

Welds began and ended at roughly 2 in. from the ends of the plate, resulting in 20 in. welds. Approximately five welds were processed per plate. Tables 1 and 2 summarize the welding parameters.
<table>
<thead>
<tr>
<th>Pin Diameter (in.)</th>
<th>Pin Length (in.)</th>
<th>Feed Rate (IPM)</th>
<th>Plate Thickness (in.)</th>
<th>Number of welds</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.300</td>
<td>0.071</td>
<td>8</td>
<td>0.375</td>
<td>9</td>
</tr>
<tr>
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<td>0.300</td>
<td>0.157</td>
<td>8</td>
<td>0.375</td>
<td>7</td>
</tr>
<tr>
<td>0.300</td>
<td>0.188</td>
<td>8</td>
<td>0.375</td>
<td>6</td>
</tr>
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<td>0.300</td>
<td>0.219</td>
<td>8</td>
<td>0.375</td>
<td>6</td>
</tr>
<tr>
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<td>0.235</td>
<td>8</td>
<td>0.375</td>
<td>10</td>
</tr>
<tr>
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<td>0.250</td>
<td>8</td>
<td>0.375</td>
<td>13</td>
</tr>
<tr>
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<td>0.250</td>
<td>8</td>
<td>0.5</td>
<td>5</td>
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<td>0.5</td>
<td>12</td>
</tr>
<tr>
<td>0.300</td>
<td>0.280</td>
<td>8</td>
<td>0.5</td>
<td>8</td>
</tr>
<tr>
<td>Pin Length (in.)</td>
<td>Pin Diameter (in.)</td>
<td>Feed Rate (IPM)</td>
<td>Plate Thickness (in.)</td>
<td>Number of Welds</td>
</tr>
<tr>
<td>----------------</td>
<td>------------------</td>
<td>----------------</td>
<td>----------------------</td>
<td>----------------</td>
</tr>
<tr>
<td>0.150</td>
<td>0.206</td>
<td>8</td>
<td>0.375</td>
<td>3</td>
</tr>
<tr>
<td>0.150</td>
<td>0.238</td>
<td>8</td>
<td>0.375</td>
<td>3</td>
</tr>
<tr>
<td>0.150</td>
<td>0.268</td>
<td>8</td>
<td>0.375</td>
<td>3</td>
</tr>
<tr>
<td>0.150</td>
<td>0.300</td>
<td>8</td>
<td>0.375</td>
<td>3</td>
</tr>
<tr>
<td>0.250</td>
<td>0.206</td>
<td>8</td>
<td>0.375</td>
<td>6</td>
</tr>
<tr>
<td>0.250</td>
<td>0.238</td>
<td>8</td>
<td>0.375</td>
<td>6</td>
</tr>
<tr>
<td>0.250</td>
<td>0.268</td>
<td>8</td>
<td>0.375</td>
<td>6</td>
</tr>
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<td>0.250</td>
<td>0.300</td>
<td>8</td>
<td>0.375</td>
<td>20</td>
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<td>0.206</td>
<td>6</td>
<td>0.375</td>
<td>1</td>
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<td>0.238</td>
<td>6</td>
<td>0.375</td>
<td>3</td>
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<td>0.268</td>
<td>6</td>
<td>0.375</td>
<td>2</td>
</tr>
<tr>
<td>0.250</td>
<td>0.300</td>
<td>6</td>
<td>0.375</td>
<td>3</td>
</tr>
</tbody>
</table>

2.3.5 Data Acquisition and Analysis

Data was recorded at a rate of 15 samples/sec. An average longitudinal force was determined from the last 200 samples (~13 sec.) for each weld. The average and standard deviation of the longitudinal force for each tool were then calculated. Force was plotted against pin length and pin diameter, and fitted with a quadratic curve. A shoulder force was estimated from the force data. The shoulder force was subtracted from the total force to obtain only pin force. Statistical studies were performed, such as mean inference testing, to better understand the data. Force distributions were then generated by taking
the derivative of the equations that describe the force curves, and plotting it against pin length.

### 2.4 Results and Discussion

Typical force data from a single weld can be seen below in figure 7. Weld parameters were 650 rpm spindle speed, and a feed rate of 8 in/min. The last 200 data points were averaged to obtain a pin force.

![Figure 7 Typical force data from a single weld](image)

With all tools, the force data consistently produced a reasonable amount of noise. Periodic variation in the data can be seen, and is likely due to tool runout.

#### 2.4.1 Longitudinal Force Distribution along Pin Length

Figure 8 shows the total longitudinal forces obtained for the various pin lengths. The error bars indicate +/- one standard deviation. The number of welds for each tool ranged from 4 – 18, as described in Table 1.
Figure 8 Results of total longitudinal force as a function of pin length

Force generally increased as pin length increased. Longitudinal force increased from 509 lbs for the shortest pin of 0.071 in, to 875 lbs for the longest pin of 0.280 in. However, at lengths of 0.098 in. and below, the force appears to be constant. The difference in force between the shortest two pin lengths, 0.071 and 0.098 in, was 3.4 lbs.

2.4.1.1 Force at Long Pin Lengths

Although force generally increased with pin length, the force decreased between 0.219 and 0.250 in. The average force dropped almost 127 lbs, from 828 lbs at 0.219 in. to 701 lbs at 0.250 in. Above 0.280 in, the force appears to be approximately constant. The longest two pin lengths, 0.265 and 0.280 in, had a force difference of only 10 lbs.

Standard deviation also generally increased with pin length, as seen in Figure 9. With the exception of length 0.188 in, the variation increased with every pin length up to 0.265 in.
Standard deviation ranged from approximately 17 lbs for the smallest pin to 109 lbs for the longest.

![Graph showing standard deviation vs. pin length](image)

**Figure 9 Standard deviation verse pin length**

2.4.1.2 Shoulder Force

There are two contributions to the total longitudinal force: the shoulder force and the pin force. This study is based on the assumption that these two forces are additive, so that:

\[
F_L(l) = F_S + F_P(l)
\]  

(1)

Where \( F_L \) is the total longitudinal force, \( F_S \) is the longitudinal force acting on the tool shoulder, and \( F_P \) is the longitudinal force acting on the tool pin.
It is assumed that shoulder force is independent of pin length. Also, pin force is assumed to be zero when pin length is zero, so total longitudinal force would then be equal to the shoulder force.

The force at the two shortest pin lengths, 0.071 and 0.098 in. were found to be nearly the same at 509 and 513 lbs, respectively. It was estimated then that the shoulder force was approximately 509 lbs. The total longitudinal force showing the shoulder force component can be seen below in Figure 10.

![Figure 10 Results of total longitudinal force as a function of pin length](image)

2.4.1.3 Pin Force

The pin force was calculated from the following equation:

\[ F_P(l) = F_L(l) - F_S \] (2)
Figure 11 shows the average pin force as a function of pin length.

![Figure 11 Calculated longitudinal pin component force as a function of pin length](image)

2.4.1.4 Force Variation

It can be seen from Figure 8 that the standard deviation is very large above pin lengths of 0.219 in. Unexpected variation was discovered for pin lengths between 0.235 and 0.280 in. At a length of 0.235 in, the average force decreased by approximately 47 lbs. In addition, it was found that at pin lengths of 0.250, 0.265 and 0.280 in, force measurements varied with the experimental period. An experimental period was 2 to 8 welds performed over a period of 1 to 3 days. The various experimental periods can be seen in Figure 12. The details for each weld set are shown in Table 3. Hypothesis testing on the inference of the means was performed on all the data sets after 0.235 in, to determine if the means were different.
Figure 12 Longitudinal force as a function of pin length, showing dates welded

Table 3 Pin length weld results summary

<table>
<thead>
<tr>
<th>Length (in)</th>
<th>Diameter (in)</th>
<th>Force (lbs)</th>
<th>Std Dev (lbs)</th>
<th>Number of Welds</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.071</td>
<td>0.3</td>
<td>509.2</td>
<td>16.5</td>
<td>9</td>
</tr>
<tr>
<td>0.098</td>
<td>0.3</td>
<td>512.6</td>
<td>22.1</td>
<td>4</td>
</tr>
<tr>
<td>0.125</td>
<td>0.3</td>
<td>555.2</td>
<td>29.8</td>
<td>6</td>
</tr>
<tr>
<td>0.157</td>
<td>0.3</td>
<td>581.4</td>
<td>45.8</td>
<td>7</td>
</tr>
<tr>
<td>0.188</td>
<td>0.3</td>
<td>651.8</td>
<td>33.1</td>
<td>6</td>
</tr>
<tr>
<td>0.219</td>
<td>0.3</td>
<td>828.0</td>
<td>53.4</td>
<td>6</td>
</tr>
<tr>
<td>0.235</td>
<td>0.3</td>
<td>781.4</td>
<td>68.1</td>
<td>10</td>
</tr>
<tr>
<td>0.250</td>
<td>0.3</td>
<td>581.2</td>
<td>18.9</td>
<td>6</td>
</tr>
<tr>
<td>0.250</td>
<td>0.3</td>
<td>837.7</td>
<td>31.0</td>
<td>4</td>
</tr>
<tr>
<td>0.250</td>
<td>0.3</td>
<td>717.1</td>
<td>49.3</td>
<td>8</td>
</tr>
<tr>
<td>0.265</td>
<td>0.3</td>
<td>875.7</td>
<td>68.0</td>
<td>2</td>
</tr>
<tr>
<td>0.265</td>
<td>0.3</td>
<td>995.5</td>
<td>40.9</td>
<td>5</td>
</tr>
<tr>
<td>0.265</td>
<td>0.3</td>
<td>782.9</td>
<td>58.9</td>
<td>5</td>
</tr>
<tr>
<td>0.280</td>
<td>0.3</td>
<td>999.3</td>
<td>38.6</td>
<td>3</td>
</tr>
<tr>
<td>0.280</td>
<td>0.3</td>
<td>800.3</td>
<td>36.9</td>
<td>5</td>
</tr>
</tbody>
</table>
At pin length 0.250 in, statistical results show that each mean at length 0.250 in. is separate and three data sets exist. At pin length 0.265 in, the low and high mean comparison yielded separate means. The pin length comparison at 0.280 in. also resulted in separate means. Statistical details can be seen in Appendix A.

Figure 13 Longitudinal force as a function of pin length with variation

Figure 13 above shows the longitudinal pin force data including the separate data sets after length 0.235 in. and error bars indicating +/- one standard deviation. Two force curves, a high and low are shown.

Some potential sources for this variation were explored in this study, and are described in Appendix B.

2.4.1.5 Force Distribution along Pin Length

Four different force distribution models were created from the data: (1) a piecewise uniform force distribution, (2) a polynomial curve fit of the forces for pins shorter than
0.219 inches, (3) multiple fits on average forces for longer pins having the same functional form as model 2, and (4) curve fits like model 3 based on the highest measured forces. Each of these models is discussed below.

2.4.1.5.1 Piecewise Uniform Distribution

A piecewise uniform force distribution can be seen in Figure 14. The width of each region is determined by the difference in length of two pins. The uniform force distribution for each region is calculated by dividing the difference in force between successive pin lengths by the difference in length of the two pins. The distribution generally increases with pin length. However, between pin lengths of 0.235 and 0.250 in. a negative distribution existed due to the measured force decrease. The negative distribution would mean that at these pin lengths, a force is acting on the backside of the pin tool, decreasing the total longitudinal pin force. It is the author’s belief that this is highly unlikely, and that the negative distribution does not really occur. Instead, it is

![Figure 14 Piecewise uniform force distributions for the average data along pin length](image-url)
more probable that when welding at pin lengths above 0.219 in, the force distribution near the shoulder is different than it is for shorter pins. If this is true, then the method of obtaining a distribution by varying the pin length, assuming additional pin length leads to additional force, does not work well for pin lengths longer than 0.219 in.

2.4.1.5.2 Curve Fit Distribution

It is highly unlikely that the distribution is discontinuous as shown in Figure 14. To obtain a smooth force distribution, a curve was fit to the force data. A second order polynomial curve was fit to the average data for short pins only, with pin length up to 0.219 in, as shown in Figure 15.

![Figure 15 Longitudinal pin force as a function of pin length with curve fit up to 0.219 in.](image)

The fit curve decreases slightly then increases up to pin length 0.219 in. The $R^2$ value for the curve was 0.973, which indicates that it is an excellent fit to the data. The curve shows a force minimum at approximately 0.093 in. For consistent analysis, the pin force is assumed to be zero below the minimum and to follow a quadratic function above the
minimum. Below 0.093 in. then, the total longitudinal force is assumed to be due entirely to the tool shoulder.

The force distribution up to 0.219 in. was generated by taking the derivative of the curve fit equation, \( y = 18864x^2 - 3494.9x + 162.8 \). The force distribution along pin length based on the curve fit can be seen in Figure 16. The distribution is zero at 0.093 in. and linearly increases to 4805 lbs/in. at 0.219 in.

![Figure 16 Force distribution along pin length up to 0.219 in.](image)

### 2.4.1.5.3 Distribution for Pin Lengths over 0.219

If, as stated above, the force distribution near the shoulder changes as the pin length becomes 0.235 in. or higher, a curve fit of the overall data would not accurately characterize the force variation and decrease. A better approximation of the distribution at these lengths may be that the functional form of the distribution is constant for all pin lengths. The functional form can be estimated from the short pin (0.219 in. and below)
data. The curve for 0.219 in. proved to be an excellent fit, and seems reasonable that the force curve for longer pins would follow a similar shape. Distributions were created for the large pins by assuming the same mathematical form with different constants. The quadratic equation that fits the 0.219 in. data is:

\[ F = 18,864L^2 - 3,494.9L + 162.8 \]  

(3)

The curve contains a minimum force value of approximately zero at length 0.093in. \((L_0)\).

Below \(L_0\), the pin force was assumed to be zero. An adjusted pin length \(L_a\) was calculated by subtracting \(L_0\) as shown in Figure 17.

![Graph showing the force as a function of adjusted pin length](image)

**Figure 17 Pin force as a function of adjusted pin length up to 0.219 in.**

The new fit curve equation was:

\[ F = 18,864L_a^2 + 13.69L_a + 0.91 \]  

(4)
The second and third terms of this fit are very close to zero and can be ignored. The functional form of equation (4) then becomes

\[ F(L_a) = A L_a^2 \]  

(5)

with A as a constant. The force distribution along a pin is obtained by differentiating equation (5) with respect to L, and substituting \( x_a \) (the distance along the pin) for \( L_a \) (the length of various pins).

\[ \lambda = 2A x_a \]

(6)

where \( \lambda \) is the force per unit length on the pin. Thus, the functional form of the force distribution is a line increasing from \( x_a = 0 \) to \( L_a \), the pin length. Below \( x_a = 0 \) the force distribution is zero. Solving equation (5) for A and substituting into equation (6) gives

\[ \lambda = 2F(L_a)x_a/L_a^2 \]

(7)

This equation is used to predict the distribution for pin lengths longer than 0.219 in.
Figure 18 Predicted distributions based on the average force data for pin lengths between 0.235 and 0.280 in.

Figure 18 shows the predicted distributions for the average force data for pin lengths of 0.235, 0.250, 0.265 and 0.280 in. Distributions were also calculated for the low and high force data for pin lengths 0.250, 0.265 and 0.280 in, and can be seen in Figures 19-21. These figures represent the distribution range between the low and high pin force data.

Figure 19 Force distribution range for pin length 0.250 in.
2.4.1.5.4 Largest Distributions

The low and high force data at long pins provides a window where a distribution will fall. The most important distributions with respect to tool design however, are the largest distributions, as they will be most critical to pin life. Figure 22 displays the distribution for pin lengths up to 0.219 in. and the largest distributions for pin lengths between 0.235
and 0.280 in. Based on this study, these seem to be appropriate distributions to model tools from for a given pin length and conditions.

![Graph showing distributed load vs pin length for different pin lengths.](image)

**Figure 22 Largest possible distributions**

2.4.1.6 Summary of Longitudinal Force Distribution along Pin Length

The distribution based on the fit curve appears to be a very reasonable distribution for pin lengths up to 0.219 in. The force increased with pin length and the $R^2$ value of 0.973 indicates the curve is an excellent fit to the data. Because of the excessive variation and force decrease after pin length 0.219 in, a fit curve does not represent the force data for long pins well. It is believed that when welding with long pin tools, forces for short pins are no longer constant, but decrease. Therefore, varying pin length to measure a distribution does not appear to work for pins longer than approximately 0.219 in. Instead, the best distribution approximation for long pins is believed by the author to be a distribution based off the fit curve for the 0.219 in. pin tool. Though this study could not accurately measure the distribution for long pin lengths, it seems very reasonable that due
to the confidence of the 0.219 in. results, they will take on a similar shape of the 0.219 in. distribution. The predicted distributions for long pins were performed on the low and high force data, therefore creating a range in which the distribution will fall. However, the largest distributions will be of most interest to tool design.

2.4.2 Longitudinal Force Distribution along Pin Diameter

Force data was collected from tools that varied in pin diameter. Pin lengths were kept constant at 0.15 and 0.25 in. Forces generally remained flat as pin diameter increased, and showed little pattern between the two pin lengths.

The results of longitudinal force as a function of pin diameter are listed in Tables 4 and 5. It should be noted that for pin length 0.250 in. and diameter 0.300 in. with a feed rate of 8 IPM, the total average force and standard deviation was used, previously calculated in the longitudinal force versus pin length study.

<table>
<thead>
<tr>
<th>Diameter (in)</th>
<th>Length (in)</th>
<th>Force (lbs)</th>
<th>Std Dev (lbs)</th>
<th>Number of Welds</th>
<th>Feed Rate (IPM)</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.206</td>
<td>0.25</td>
<td>659.9</td>
<td>-</td>
<td>1</td>
<td>6</td>
</tr>
<tr>
<td>0.238</td>
<td>0.25</td>
<td>694.9</td>
<td>25.3</td>
<td>3</td>
<td>6</td>
</tr>
<tr>
<td>0.268</td>
<td>0.25</td>
<td>578.7</td>
<td>0.1</td>
<td>2</td>
<td>6</td>
</tr>
<tr>
<td>0.300</td>
<td>0.25</td>
<td>643.2</td>
<td>31.6</td>
<td>3</td>
<td>6</td>
</tr>
</tbody>
</table>

Note: Only one weld was measured for pin diameter 0.206 in. and 6 IPM, as the tool failed on the second weld.
### Table 5 Pin diameter weld results summary – Feed Rate 8 IPM

<table>
<thead>
<tr>
<th>Diameter (in)</th>
<th>Length (in)</th>
<th>Force (lbs)</th>
<th>Std Dev (lbs)</th>
<th>Number of Welds</th>
<th>Feed Rate (IPM)</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.206</td>
<td>0.25</td>
<td>689.9</td>
<td>18.6</td>
<td>6</td>
<td>8</td>
</tr>
<tr>
<td>0.206</td>
<td>0.15</td>
<td>691.5</td>
<td>6.4</td>
<td>3</td>
<td>8</td>
</tr>
<tr>
<td>0.238</td>
<td>0.25</td>
<td>728.1</td>
<td>19.2</td>
<td>6</td>
<td>8</td>
</tr>
<tr>
<td>0.238</td>
<td>0.15</td>
<td>648.7</td>
<td>10.1</td>
<td>3</td>
<td>8</td>
</tr>
<tr>
<td>0.268</td>
<td>0.25</td>
<td>670.5</td>
<td>38.3</td>
<td>6</td>
<td>8</td>
</tr>
<tr>
<td>0.268</td>
<td>0.15</td>
<td>542.1</td>
<td>30.2</td>
<td>3</td>
<td>8</td>
</tr>
<tr>
<td>0.300</td>
<td>0.25</td>
<td>701.1</td>
<td>103.4</td>
<td>20</td>
<td>8</td>
</tr>
<tr>
<td>0.300</td>
<td>0.15</td>
<td>647.8</td>
<td>51.4</td>
<td>3</td>
<td>8</td>
</tr>
</tbody>
</table>

#### 2.4.2.1 Force Change with Pin Diameter

It was anticipated that the force would increase with pin diameter; however the results did not support this hypothesis (Figure 23). Force did not prove to be a strong function of pin diameter, as the greatest variation in force between the smallest and largest diameter pin was less than 7%. At a length of 0.250 in. and 8 IPM, force fluctuated between 670 and 728 lbs, with little consistency. The force curve for pin diameter of 0.250 in. at 6 IPM follows the same basic shape as the curve at 8 IPM, but with a slightly smaller magnitude. It was thought that since much variation took place at pin length 0.250 in. during the pin length welds, that perhaps a shorter pin would provide better results. But, results at 0.150 in. pin length at 8 IPM proved equally inconsistent. It appears then that varying the pin diameter is not a feasible way to obtain the radial force distribution.
2.5 Conclusions

A method has been presented for measuring the longitudinal force on the pin portion of an FSW tool. For the tool geometry and tilt angle studied, the pin is responsible for less than half of the longitudinal force on the tool, depending on tool length.

The measured pin force data was analyzed to determine force distributions along the length and across the diameter of the pin. Detailed conclusions from both of these analyses are listed below.

2.5.1 Pin Length

- Longitudinal force increases with pin length up to 0.219 in.
- Between the lengths of 0.219 and 0.280 in, there is unexpected variation in the force-pinch length curve.
For pin lengths of 0.250, 0.265 and 0.280 in, two or three separate data groups exist at each length. Data groups have proven to be unrepeatable, and vary only with time.

- Force distribution along pin length increases linearly up to 0.219 in.
- The method of varying pin length to estimate force distribution does not appear to work well for pin lengths longer than 0.219 in.

2.5.2 Pin Diameter

- Longitudinal force is not a strong function of pin diameter at 650 rpm and 6-8 IPM.
- Force changes with feed rate between 6 and 8 IPM, but force-diameter curve has same general shape at both feed rates.
- The method of varying pin diameter does not appear to work well for estimating force distribution along diameter of pin.
CHAPTER 3: RECOMMENDATIONS FOR FUTURE WORK

Several recommendations for additional areas of research are listed below:

1. The pin tools used in this research were a smooth cylinder, having no welding enhancement features such as threads, flats or tapers. This pin tool design added simplicity to the study; however it is not representative of the pin tools used in typical welding applications. To create a more practical force distribution, forces should be measured with a pin tool that contains some of these pin features.

2. Although force variation occurred at long pin lengths in this research, it is not known whether this phenomenon occurs under other welding conditions. An experiment comparing pin force behavior with different welding materials, tools and parameters should also be performed.

3. A variable that was not measured in this research was temperature. Since the temperature of FSW tools and welding material is directly related to tool forces, quantifying these values may be helpful in better understanding the force variation.
References


Appendix
APPENDIX A: HYPOTHESIS TESTING

Hypothesis testing details were as follows:

1. The parameters of interest were the three means from the data sets at both 0.250 and 0.265 in, and the two means at 0.280 in. The means are identified as follows:

<table>
<thead>
<tr>
<th>Length (in)</th>
<th>Force (lbs)</th>
<th>Mean Id.</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.250</td>
<td>837.7</td>
<td>( \mu_{1,0.250} )</td>
</tr>
<tr>
<td>0.250</td>
<td>717.1</td>
<td>( \mu_{2,0.250} )</td>
</tr>
<tr>
<td>0.250</td>
<td>581.2</td>
<td>( \mu_{3,0.250} )</td>
</tr>
<tr>
<td>0.265</td>
<td>995.5</td>
<td>( \mu_{1,0.265} )</td>
</tr>
<tr>
<td>0.265</td>
<td>875.7</td>
<td>( \mu_{2,0.265} )</td>
</tr>
<tr>
<td>0.265</td>
<td>782.9</td>
<td>( \mu_{3,0.265} )</td>
</tr>
<tr>
<td>0.280</td>
<td>999.3</td>
<td>( \mu_{1,0.280} )</td>
</tr>
<tr>
<td>0.280</td>
<td>800.3</td>
<td>( \mu_{2,0.280} )</td>
</tr>
</tbody>
</table>

2. The null hypothesis \( (H_0) \) was \( \mu_{1,0.250} = \mu_{2,0.250} = \mu_{3,0.250}, \ \mu_{1,0.265} = \mu_{2,0.265} = \mu_{3,0.265}, \ \mu_{1,0.280} = \mu_{2,0.280}. \)

3. The alternative hypothesis \( (H_1) \) was \( \mu_{1,0.250} \neq \mu_{2,0.250} \neq \mu_{3,0.250}, \ \mu_{1,0.265} \neq \mu_{2,0.265} \neq \mu_{3,0.265}, \ \mu_{1,0.280} \neq \mu_{2,0.280}. \)

4. \( \alpha = 0.05 \)
The P-values for all pairwise comparisons are shown below:

<table>
<thead>
<tr>
<th>Level Sample</th>
<th>P-value</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\mu_{1,0.250}$</td>
<td>$\mu_{2,0.250}$</td>
</tr>
<tr>
<td>$\mu_{2,0.250}$</td>
<td>$\mu_{3,0.250}$</td>
</tr>
<tr>
<td>$\mu_{3,0.250}$</td>
<td>$\mu_{1,0.250}$</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Level Sample</th>
<th>P-value</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\mu_{1,0.265}$</td>
<td>$\mu_{2,0.265}$</td>
</tr>
<tr>
<td>$\mu_{2,0.265}$</td>
<td>$\mu_{3,0.265}$</td>
</tr>
<tr>
<td>$\mu_{3,0.265}$</td>
<td>$\mu_{1,0.265}$</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Level Sample</th>
<th>P-value</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\mu_{1,0.280}$</td>
<td>$\mu_{2,0.280}$</td>
</tr>
</tbody>
</table>
APPENDIX B: POTENTIAL SOURCES OF VARIATION

One possible source of variation that was thought to contribute was shoulder depth inconsistencies while welding. A test was run with a tool 0.219 inches in length and 0.300 inches in diameter at various shoulder depths to determine longitudinal force verses shoulder depth. From weld visualization, the flatness fluctuation of a typical workpiece yielded a possible shoulder depth variation up to +/- 0.010 in. For shoulder depths greater than 0.010 in, excess flash or weld plowing can be observed. For depths less than -0.010 in, narrow welds due to lack of shoulder penetration or low material volume in the shoulder can be detected. See Figure below.

Figure B1 Photo showing welds with shoulder depth of 0.010 in. (top) and -0.010 in. (bottom)
From Figure B2, this translates to a force variation of roughly 80 lbs. The difference between the high and low data sets at pin length 0.250 in. is 257 lbs, more than three times the force variation due to plate flatness. Also, it is assumed that this variation would exist at all the pin lengths, not just at 0.235 in. and greater. Therefore, it appears that shoulder depth fluctuation is not the cause of the force variation.

![Figure B2 Longitudinal force as a function of shoulder depth](image)

It was also thought that perhaps an interaction existed between the anvil and the pin for pin lengths of 0.250 and larger, so 0.500 in. thick aluminum plate was welded and compared. The results showed that the difference in force was insignificant – an approximate 2% change at 0.250 in.