Friction-stir riveting: mechanical testing of friction-stir riveting

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University of Toledo
A Thesis

Entitled

Friction-Stir Riveting: Mechanical Testing of Friction-Stir Riveting

By

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Submitted to the Graduate Faculty as partial fulfillment of the requirements for the Masters of Science Degree in Mechanical Engineering

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An Abstract of

Friction-Stir Riveting: Characteristics of Friction-Stir Riveted Joints

and Mechanical Testing

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In automobiles fields, material weight is very important, so in order to reduce the weight, a lot of light metals are used more and more frequently in the automobile industry, such as aluminum and magnesium alloys. But in large-scale applications, there are some difficulties in welding them. In this situation, new joining methods are needed and developed, for example friction-stir welding and self-piercing riveting.

The University of Toledo has developed a new joining method called hybrid friction-stir riveting. This method can be used to join both similar and dissimilar metals. This kind of joint is created by spinning and pressing a solid rivet into layers of sheet metals. It has the characteristics of both friction-stir welding and self-piercing riveting.

In this process, sheet metals are jointed by rivet and a cohesion zone near the steel rivet through the stirring process. The joining strength comes from the mechanical interlocking, adhesion, and solid bonding. The joint quality is affected by tooling, joining process and the geometry of the rivet. For
example, the rivet should provide as much interlocking to the sheets as possible, meanwhile, its concave area should be filled with the mixed aluminum materials. In the experiment, spindle speed and feed rate were found affect the joint quality. These effects are discussed through both experimental and numerical ways. A best choice of the joint geometry was performed and experimentally verified.


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Chapter 1

1. Introduction

1.1. Background Introduction

There are many ways to join metals based on the materials and applications. Welding and riveting are two different methods to join metals with different principles. Welding includes arc welding, gas welding, resistance welding, and friction-stir welding. In these processes, chemical reactions usually occur between metals when creating a joint. Riveting provides mechanical fastening because it can form an interlock between metals. Each of the methods has both advantages and disadvantages. So methods are usually chosen based on cost and overall considerations of application. Friction-stir welding and self-piercing riveting are two common methods to form a mechanical joint between workpieces. As mentioned above, light metals are more and more frequently used in the automotive industry such as aluminum and magnesium alloys. Welding these kinds of metals requires more advanced methods because of their special chemical and physical properties. In past years, resistance spot welding has been very common and popular, but it has many difficulties in welding because of the physical properties of aluminum and magnesium or other kinds of light metals [1]. Resistance spot welding causes high thermal expansion in both solid and liquid states and large volume expansion due to melting [2]. Also, the high chemical affinity of aluminum for copper results in short
electrode life in welding aluminum is a problem [3]. In the following sections some characteristics of alternative mechanical joining methods such as self-piercing riveting and friction-stir welding will be shown. Then the friction-stir riveting process will be introduced.

### 1.1.1. Self-piercing Riveting

First of all, a rivet is used to join pieces of metals, plastics, wood, or other materials. A hot rivet can go into the metal easily and when the rivet cools, it shrinks and tightly joins all parts. The self-piercing process is a clean and simple method of joining sheet metals without the demand for pre-punched or pre-drilled holes. It creates a very high degree of joint integrity. The self-piercing joint has higher strength compared with the strength of a spot welded joint. It is a high-speed mechanical fastening process for joining sheet metals, typically steels and aluminum alloys. It is a one-step technique, usually using a semi-tubular rivet to clench the sheet metals into a mechanical joint. The rivet tail should not pierce the material.

The advantages of self-piercing riveting are shown as follows:

1. No need for pre-punched or pre-drilled holes
2. It can significantly reduce assembly time and cost of parts
3. Piercing and fastening are in one step
4. Automation enables high speed operation and efficiency
5. Dissimilar materials can be joined
6. Coated or painted materials can be joined
7. Permanent assembly is ensured
8. Great mechanical strength and fatigue performance is achieved
9. Highly repeatable results
(10) The appearance of the welded material is uniform and enhanced.

(11) Self-sealing joints are air-tight or water-tight.

Compared with the spot welding, the self-piercing riveting has more advantages:

1. The material properties do not change in the self-piercing process.
2. The joint formed by self-piercing is stronger than that formed by spot welding.
3. Different kinds of materials can be joined together.
4. The metals have less deformation caused by stress and strain.

Self-piercing riveting is a good way to join aluminum. It overcomes the difficulties in common welding processes. Self-piercing riveting forms a mechanical interlock. Spot welding can cause metallurgical reactions [4-6]. In self-piercing riveting, a semi-tubular rivet is pressed into sheets which are placed on a die. A SPR joint is shown in Figure 1-1. The rivet goes through the first sheet and forms a joint with the second sheet below. The riveted joints created through a dynamic self-piercing riveting process have mechanical strengths similar to or higher than spot welds on one type of aluminum alloy [7]. Self-piercing riveting can be used to join aluminum alloys, but it is not suitable to join magnesium because of the low ductility property of magnesium alloys [8]. Self-piercing riveting is an attractive way to join difficult-to-weld materials. It can replace spot welding. The joint does not cost much, so it can be widely used in the automotive industry. A die is placed under the sheets to be riveted. When the rivet is being pressed into the sheets, the material fills the die cavity; then, the shape of the die pushes the rivet inside the metal, causing the sheet material to be locked together by the rivet as seen in Figure 1-1. Figure 1-1 gives the instruction for the cross section of a self-piercing rivet joint: the rivet looks black. The top sheet is a 2 mm thick AA 5754 aluminum sheet, and the bottom sheet is a 1.4 mm
thick sheet of steel. The steel appears black because it was polished. The appearance of polished steel is better than the appearance of polished aluminum. Light is reflected off the aluminum. The aluminum is scattered, so it is convenient to take a photograph. Light is reflected off the steel, and the light does not scatter as much as with aluminum. Compared with the polished aluminum, the polished steel gives a mirror like reflection. The steel has a specular surface that reflects the light from one direction. Because of the mirror like reflection, the steel appears dark, as no light from the steel goes into the camera. The rivet passes through the bottom sheet of steel. The shape of the sample is formed because of the die cavity under the sheet metal. The die cavity allows the rivet to go through the sheet, which helps to form a good joint. Self-piercing riveting can be used to join dissimilar metals as in Figure 1-1. Self-piercing joints can be produced cheaply and in large quantities. It also has a high level of consistency, so it can be widely used in the automotive industry. Some limitations should be noticed when joining sheets such as magnesium alloys. Compared with aluminum, magnesium alloys are brittle. Self-piercing can cause fracture in the place where the stress is gathered when the rivet is being pressed into the sheets of magnesium alloys.
Friction-stir welding is another popular alternative method used for joining difficult-to-weld metals, and it can be used for joining light metals. This method usually uses a rotating cylindrical-shouldered tool with a profiled pin that transverses along the joint line between two sheets [9-10]. The spinning movement of the tool gathers frictional heat, which helps to soften and mix the material in the stirred area. Then a solid bond is created by mixed material. These processes do not imply melting and solidification, so they have less negative influences on the physical properties of the metal. Figure 1-2 (a) shows a friction-stir welded seam track [11]. This method is successfully applied to joining aluminum and magnesium [12-15], and its negative effects are apparent. Tight and rigid fixtures of the workpieces cause difficulties in real applications. A related technique is called friction-stir spot welding. The process is quite similar to the friction-stir welding, but with a vertically feed rotating probe [16]. Figure 1-2 (b) shows a joint formed by this joining method.
1.1.2. Hybrid Friction-stir Riveting

Hybrid Friction-stir riveting is a new method to join light metals. It can be used to join both aluminum and magnesium alloys. Figure 1-3 is a joint created by friction-stir riveting. In this process, a rotating rivet is pressed by a mill. The rivet goes through the top sheet and part of the bottom sheet, and it creates a mechanical interlock by leaving the rivet inside the sheets. Heat is produced due to spinning and rotating; the heat softens the metals; and the rivet goes through the sheets without causing metallurgical changes. The joint provides strength that comes from the mechanical interlock; the stirred and mixed zone of the metals in the vicinity of the rivet; and the solid state bonding between the sheets around the mixed zone.
Figure 1-3 Hybrid friction-stir riveting joint
Chapter 2

2. Friction-stir Riveting

2.1. Process Introduction

The hybrid friction-stir riveting was proved to be viable by the Material Joining Laboratory at the University of Toledo. After many experiments were done, the rivet geometry, details of the driver and clamping, and die size were determined. A CNC mill was used for the rivet penetration process. All parts are assembled as shown in Figure 2-1. First of all, the rivet is squeezed between the driver and the top sheet. This step is to ensure that the joint is at the right position as designated. Then the driver begins rotating without feeding, the rivet spins as fast as the driver, and they have the same rate. The rivet is tightly touched on the top sheet, so heat begins to generate around the rivet bottom flange. It helps the metal to soften and allows the rivet to penetrate. This step is called preheat, and it lasts 1 minute. Next, the driver presses the rivet while rotating with the preset speed and feed rate until it reaches the designated depth. Then the driver stops, and the whole process is completed.
2.2. Joint Characterization

The rivet, the mixed zone around rivet trunk, and the solid bonding between two sheets determine the quality of the joining, so the characterization of friction-stir riveting comes from these three aspects. The solid bonding area is easy to damage and due to the etchant used for metallographic analysis. These two aspects can be neglected. So solid bonding part is the most important aspect of these three. Thus, the riveting process needs to be discussed. In hybrid friction-stir riveting, the feed rate, spindle speed, feed depth, and the preheating time can be easily controlled. The preheating time does not have a significant effect on the process. The rotation speed ranges from 500 rpm to 3000 rpm, and the feed rate starts from 0.05 inch/min and then rises 0.05 inch/min. The thickness of the two sheets is 4 mm (2mm each), so the depth can not beyond 4mm.
2.2.1. Characteristics of Riveted Joints

As shown in Figure 2-2, it is a microscopic picture which shows the cross section of a riveted joint formed by using a large die and rivet penetration of 2.4 mm. This picture shows the mixed area in the vicinity of the river trunk. This area is created by the rotating rivet. The rivet stirs and mixes the metal around the rivet causing the two sheets to be welded together. We can assume that the mixed zone actually performs as one piece of metal after being mixed together, because the metal melts by the action of rivet rotation, and the material is united after the melted material cools down. The strength of the rivet is determined by the junction where the surfaces meet at the end of the interface. The cross section areas in the mixed zone are measured by the vertical distance to the end of the interface from the upper rivet head to the extension cord of the bottom sheet. These two distances are denoted as $d_t$ and $d_b$. The size of the mixed zone can be described by the distance between the end of the interface on both sides of the rivet, $w$. The size of the mixed zone is easier to be measured by the distance between the ends of the interface and the center line, so the total length $w$ will be used to describe the joint.
2.2.2. Effect of Riveting Die

As mentioned above, there are three aspects that will affect the quality of the joint. Two aspects of the three are the main factors, and they are: mechanical interlocking and the mixed zone around the rivet. A good joint should have a large interlocking and a wide mixed zone, and the position of the interfaced ends are significant. They will affect the quality of the joint by two aspects: the deformation and fracture behavior of the sheets. The closer the end of the interface is to the edge of the rivet head, the easier the fracture will occur. This conclusion will be proved in the testing section.

The rotating and feeding process softens the metal around the rivet and then squeezes the metal out of the sheets. The metal flows upward. It can not go downward easily because the clamping process makes the sheets closely attached to each other tightly. The end of the interface is pushed upwards if it is not controlled.
How to control this process? A lot of experiments were operated and finally the easiest way was found, and it consists of the use of a die. The die will lead part of the squeezed metal flow into it. Three steps were made to find out what is the proper size. The first one is a flat piece of steel; the second one is a small die; and the third one is a large die. The cavity volumes of the second and third ones are 7.33 mm³ and 21.2 mm³. All other parameters were preset and fixed, and the use of the largest die was then determined to be the best one. Namely, the large die with cavity volume of 21.2 mm³. It can create a lower end of the mixed zone.

A flat interface is desirable, and we assume that \( w \) will not be affected by die size significantly.

Figure 2-3 shows the joint formed without using a die. It is obvious that the bottom of the sheet is flat, and a lot of metal is squeezed upwards out of the sheet, and the interface apparently curled up. As shown in Figure 2-3.

Figure 2-2 Friction-stir riveting joint without using a die
The second attempt is using a small die with cavity volume of 7.33 mm$^3$. We found out that some of the squeezed metal flowed into the die. As shown in Figure 2-4, there is less squeezed metal out of the sheets than the one formed without using a die, and interface curling up reduced.

![Figure 2-3 Friction-stir riveting with small die volume](image)

The third experiment is using a large die with cavity volume of 21.2 mm$^3$. As shown in Figure 2-5, much less squeezed metal comes out of the metal sheets, and the interface appears to be flat. So, the conclusion is that the sizes of dies significantly affect the interface, and in other words, the size determines the quality of the friction-stir riveting joint.
2.2.3. Process Parameters

After a lot of experiments being done, we found out that a good joint can be formed when spindle speed, feed rate, and feed depth were controlled.

2.2.4. Effect of Process Parameters on Joint Formation

We found out that the rivet’s depth of penetration and the shape of rivet affect the quality of the joint. The spindle speed affects the preheat time, and the feed rate affects the time the designated depth is reached. The combination of them were considered. We used the ratio of spindle speed and feed rate, which as mentioned before is, the width of the mixed zone $w$, the thickness of the sheets around the rivet $dt$, and $db$. Some experiments were operated to find out the relationship between these parameters. The depth of feed was fixed, and we used different combinations of spindle speed and feed rate. Figure 2-6 shows the relations between the heating ratio and parameters. Figure 2-6(a) shows the relationship between the width of the mixed
zone and the heating ratio. We can see little difference in the width with different heating ratios. The values of the width of the mixed zone are about 6 mm with little residuals. The diameter of the bottom of the rivet is 6 mm. It is similar to the width of the mixed zone. We can conclude that the mixed zone is mainly created by the rivet, and it has no relationship to other parameters. Figure 2-6(b) shows that all the geometric characteristics have a dependence relationship. The measurements change significantly when the heating rate is low. It is also reflected in Figure 2-6(a) when the width of mixed zone changes around the value of 7 mm at the beginning, and then it goes down around 6.6 mm when the heating ratio is increased. Finally, we found out that the best combination of these parameters appears around the heating ratio of 40000 rpm*min/in. When the depth of feed increases, a better joint can be achieved. At last, the combination of 2000 rpm spindle speed and 0.05 in/min feed rate was used in future testing. These results were made by previous researchers.
2.2.5. Effect of clamping strength

Clamping strength is a very important parameter that affects the quality of a joint. At first, the downward force given by the rivet through the driver was assumed sufficient during the riveting process, then clamped in order to prevent the two aluminum sheets from moving in a horizontal direction, but the result is not desirable because the sheet metals separated. This situation is shown in Figure 2-6 and Figure
2-7. The separation of two metal sheets was caused by insufficient downward force. In other words, the strength given by the rivet through the driver is not enough. After a lot of experiments were conducted, the means of clamping was determined. This technique involves a steel plate clamped tightly to the sheets to offer a downward force evenly to the sheet metal. A washer was welded to the steel plate in order to offer a compressive force to the sheet metals surrounding the rivet to prevent the separation, as shown in Figure 2-8 and Figure 2-9. The steel plate is shown in Figure 2-10-1, Figure 2-10-2, and Figure 2-10-3, the steel plate is cut from one side, and in this way, the rivet and driver set can be placed easily.

Figure 2-6 Sheets separation
Figure 2-7 Insufficient clamping

Figure 2-8 Final clamping technique with washer [18]
Figure 2-9 Final clamping technique with washer

Figure 2-10-1 Clamp steel top view
Is there any effect on the quality of the joint if different strength levels are applied? Some experiments were operated to find out the answer. Three levels were arranged. In these experiments, a torque was used to ensure the expected force levels.
In the first experiment, clamps were given 10 foot pound force; then, the result is undesirable, and the two sheet metals separated. This joint was not formed. The reason why they separated is that the clamp downward force is not enough to fix the sheet metals. The sheet metals were not clamped to each other tightly. Horizontal movement occurred during the process. This reason led to failure. As shown in Figure 2-11-1. Then the second experiment was operated, and this time, the clamps were given 20 foot-pound clamping torque, the result seems good, but observed in a microscopic photo, one can see that the interface curled up, which is undesirable. The result is shown in Figure 2-11-2. The last experiment was then conducted, one can see the interface is almost horizontal, as shown in Figure 2-11-3, and the quality of the joint is great. The strength tests are displayed in further sections. Based on all the three experiments, we can conclude that the clamping force is a very important parameter that will affect the quality of the joint.

Figure 2-11-1 Joint formed with 10 foot-pound clamping torque
Figure 2-11-2 Joint formed with 20 foot-pound clamping torque

Figure 2-11-3 Joint formed with 30 foot-pound clamping torque
2.2.6. Rivet heat treatment

Rivets need heat treatment to avoid fracture at the rivet stem during insertion. The steps of heat treatment are shown as follows, in which a furnace will be used. As seen in Figure 2-11-4.

1. Preheat-heat the rivets to 1200°F for 30 minutes.
2. Hardening-heat the samples to 1500°F for an additional 60 minutes.
3. Quench-quench in oil at room temperatures, then clean oil off samples.
4. Temper-heat rivets to 400-500°F and hold for 2 hours.

![Furnace](image)

Figure 2-11-4 Furnace

2.2.7. Sample preparations

In order to get a micro observation of the joint, a sample should be carefully made. After the friction-stir riveting process, the sample should be cooled by air in
order to let the rivet shrink and pull the joint tightly. The steps of making a specimen are shown below.

(1) Cutting: Cut along the line shown in Figure 2-12-1

![Figure 2-12-1 Cut a riveted joint [18]](image)

The rivets were cut by an abrasive disc cutter. In order to cut along the half line of the rivets and also in order to get a good specimen, different section lines were chosen to give a good view of the cross section. Figure 2-12-1 shows the positions of cutting two identical rivets in half by an abrasive cutter. The bold black line stands for the disc cutter. One should pay more attention when cutting the rivets. One cannot cut the rivet just along the center line, but should leave at least 1-2 mm offset. Because of the loss of material during disc cutting, grinding and polishing phase, the finished cross section will not be at the center of the rivet. An abrasive cutter will be used. As seen in Figure 2-12-2.
Figure 2-12-2 Abrasive cutter

(1) After the sheets are cut along the line, cut the redundant parts of the metals, and make it a cuboid with half the rivet inside. The size should be neither too big nor too small. For the cuboid will be put in the mounting press device, shown in Figure 2-12-3, the side face of the cuboid should be placed in the center of the sample.
(2) Heat with the mounting press device and fill in the bakelite powder, the bakelite powder is shown in Figure 2-12-4, the side with rivet should be placed downward, in this way, one can observe the cross section after it is done. It also makes the next steps easier. The heating time will be 12 minutes. The tube needs to be cooled after heating in order to repeat the previous steps of step 3 to make more samples. The cooler is shown in Figure 2-12-5. Put the cooler in water before use in order to get a good result.
(3) Abrasion: A belt surfacer will be used to achieve a rough grinding. This step is to remove the redundant material due to cutting, along with the baked powder on the sample surface. The machine is shown in Figure 2-12-6.
(4) Grinding: An abrasive paper grinder will be used. The order for grinding is from the left to the right as seen in Figure 2-12-7. The number of the abrasive paper stands for its roughness. The following abrasives were used: grit 240, grit 320, grit 400, and grit 600, and effects on the samples were examined by eye and also observed by microscope to ensure fine surface quality.
(5) Fine grinding: The sample will be polished on the cloth wheel blades. Gamma alumina powder 0.3 will be used first for polishing and gamma alumina powder 0.05 will be used in the last step to get a perfect surface, as seen in Figure 2-12-8. Samples should be observed every 20 to 30 seconds to see whether it has acceptable results without scratches. The gamma alumina powder should be used after dilution. The matching proportioning of powder and water is about 1:10. The cloth wheel blade is shown in Figure 2-12-9.
Figure 2-12- 8 Gamma alumina powder
2.2.8. Material flow, and interface geometry at different depths of penetration

As the thickness of the sheet is 2 mm for each, two sheets have a total thickness of 4 mm. In order to make two sheets welded together, the depth of penetration should start from at least 2 mm. Five experiments were conducted with depth ranges from 2.4 mm to 4.0 mm with an increment of 0.4 mm for each. All the photos are shown in Figure 2-13. Actually all the rivets in Figure 2-13 are identical. The differences that appeared are caused by different cutting angles of the rivets. That is why the differences appear.
All photos in Figure 2-13 were taken with the identical die, identical rivet penetration, identical 2 mm thick aluminum, identical feed rate, identical feed speed, and identical clamping force. Figure 2-13-1 shows a rivet with 2.4 mm depth of penetration. One can see that the lower sheet metal did not bond with the upper sheet metal. The material filled the die. The aluminum deformed and took the shape of the die. This is why a rivet with 2.4 mm depth of penetration did not pierce a sheet of aluminum with a thickness of 2 mm. One can also see the separation of the sheets. From the photos of 2-13, one can see that the softened aluminum begins to flow back to the rivet stem after the rivet bottom flange passes through the sheet. Figure 2-13-2 shows a rivet penetrating to a depth of 2.8 mm. The upper aluminum sheet does bond with the lower sheet, but one can see that the interface of the specimen curls up, and a separation appears. As the interface approaches the rivet from the left and the right, the interface on the left side curled upward, and the interface on the right side also curled and separated. This means that the rivet does not fully pierce the sheet metals, but it forms a weak joint between the two aluminum sheets merely from the heat generated and compressive loading applied during the riveting process. The aluminum flowed back towards the rivet stem more than that in Figure 2-13-1. The stirred aluminum started to flow back to the rivet head. It led the aluminum to flow to the rivet stem. The lower sheet of aluminum deformed under the loading applied by the rivet, and the lower surface takes the shape of the die in this experiment. Figure 2-13-3 shows a rivet with 3.2 mm depth of penetration. The interface of the sheets from left to right still curls upward, but in this stage the interface curls less than that in Figure 2-13-1 and Figure 2-13-2. The lower sheet layer deforms more and gets closer to the die, and the material fully fills the die. One can notice that the rivet fully pierced the upper layer to the lower layer. The material flowed back to the rivet stem.
more than in those figures shown by previous photos. But one can still see the separation of the sheet metals on the left sides and also on the end of right sides. When it is increased to a depth of 3.6 mm as in Figure 2-13-4, the die appeared completely filled. The rivet completely penetrates the top sheet layer of aluminum throughout the entire width of the rivet bottom flange. At this stage the die was completely filled, and the rivet completely penetrates through the top layer, and pierces the bottom sheet layer. One can see that the interface is now approximately horizontal, with a slight upward curve. This is a desirable and preferable result. Figure 2-13-5 shows a rivet penetrating to a depth of 4.0 mm.

Figure 2-13-1 A joint with penetration of 2.4 mm
Figure 2-13- 2 A joint with penetration of 2.8 mm

Figure 2-13- 3 A joint with penetration of 3.2 mm
From the figures above, one can see that the interface of the joint with 3.6 mm penetration is horizontal which is desirable. This joint should have the best quality. In order to certify this conclusion, a series of experiments were conducted, the results will be shown in the next section.
Chapter 3

3. Tensile test of friction-stir riveting

3.1. Tensile test introduction

The Friction-stir riveting was introduced in previous sections. As mentioned before, the strength comes from solid bonding, the mechanical interlock, and the stirred and mixed zone. The tensile test will provide some statistics to show the performance of the friction-stir riveting joint. In tensile test of friction-stir riveting, some aspects should be discussed.

Testing a specimen is different from testing unvarying materials because of the geometric characteristics of the weldment. A weldment is usually considered a whole part; therefore, its strength is often expressed by load instead of stress, and by displacement instead of strain.

In mechanical testing, the testing procedures and sample preparation are important aspects. Many difficulties of testing friction-stir riveting joints are related to the transmitted conformation of friction-stir riveted joints. Because a friction-stir riveted joint connects two offset sheets with a limited-sized joint that is relatively less stiff than the sheets, it is the place where most rotations occur during the testing process. The stress concentration caused by the notch-like riveted joint determines the deformation and fracture mode when a sample is loaded. Therefore, testing results are frequently affected by the dimensions of the sample, in addition to the joint’s strength.
In spot welding, tensile test is commonly carried out to gain the basic data on the strength and ductility of materials. In tensile tests of uniform materials, a specimen is subject to an increasing uniaxial load, and the elongation and the load of the specimen are monitored. The test results are used to plot the stress-strain curves, in which the stress and strain are calculated from the original area and original gauge length of the specimen. These curves are useful for determining the material’s properties, like yield stress and ductility.

In friction-stir riveting samples, the term stress is meaningless for describing a joint’s strength for the reason mentioned in previous paragraphs. The entirety of a friction-stir riveted joint should be considered when it is measured for quality. Therefore, load and displacement, instead of stress and strain, are usually used for describing a joint’s quality.

Beside the peak load and ductility, the mode of final failure should also be monitored. In spot welding, the most commonly monitored parameter in tensile test is the peak load. However, the displacement at the peak load and corresponding energy should also be monitored. The displacement at the peak load indicates the ductility of the material, and the energy is related to the energy-absorbing capacity of a friction-stir joint. The displacement and energy should be calculated by the area under the load vs. displacement curve and, therefore, like the maximum displacement[1]. Unlike spot welding, friction-stir riveting does not involve much material elongation, so the displacement and energy should be calculated by the area under the load vs. displacement curve. The displacement should be considered where the load is 0N because it can fully describe the joint’s load bearing capacity.

As most joint quality inspection gains only measurable geometric quantities, it is desirable to study from the measurements the strength level of a friction-stir joint. A
very common way to quantify joint quality is to build the relationship between joint property and friction-stir riveted joint strength. Because the parameters in joining processes are most common measurements, and the tensile testing is mostly operated in practice, the main work is, therefore, on the relationship between the parameters and tensile testing strength.

The peak load in tensile testing is the most popular measurement. It shows the maximum amount of loading a joint can bear, so it provides important information to designers and other users. However, one can not get any information from such measurements on ductility, nor the performance of such a joint under dynamic, instead of static loading.[19] A quantity related to the bearing capacity of a joint should be defined in order to fully describe the strength of a friction-stir joint under either static or dynamic loading.

3.2. Sample dimensions

The dimensions of testing samples are not uniform, which may cause confusion in testing.

The sample dimensions were determined as Figure 3-1. This dimensions are actually used in spot welding, but we can still use the same dimensions for friction-stir riveting due to some similarities between the spot welding and friction-stir riveting. They are both spot joints. In spot welding, sheet metals are held together under pressure exerted by electrodes, and in friction-stir welding, the sheet metals are held by clamps and the driver. In spot welding, the thickness of the sheets typically ranges from 0.5 to 3 mm. In friction-stir riveting experiments, the thickness is 2 mm. In spot welding, electrodes are used to concentrate welding current into a “spot,” which forms a spot joint. In friction-stir riveting, the driver presses the
rotating rivet into the sheet metals, and it forms a “spot” joint. Specimen size is an influential factor in testing. Size determination is very important, different sizes lead to different testing results. Sample size determination references are shown in Figure 3-2.

Shear load vs. weld diameter:

(1) \( P = 120 d^2 \) (\( P \) in N, \( d \) in mm) [20]

(2) \( P = (0.12 t - a) d \) (\( P \) in kN, \( t \) and \( d \) in mm)

\( a = 0.06 \) for weld pull-out, \( a = 0.12 \) for weld fracture [21]

![Sample dimensions](image)

Figure 3-1 Sample dimensions

The sample dimensions should be determined by some critical standards, and the reference information is shown in Figure 3-2-1 to Figure 3-2-4. [22]

For instance, a survey of standards and specification shows significant differences in testing specimen sizes for tensile tests. In figure 3-2-3, both width and length vary remarkably in practice among professional organizations. Figure 3-2-3 shows the sample size recommendations of the American National Standards Institute (ANSI) and the American Welding Society (AWS) [23], the military [24], and the International Organization for Standardization (ISO) [25]. An obvious difference
exists in both width and overlap, with no such apparent variance in sample length. Similar differences can be seen in sample sizes of aluminum alloys. Generally, there is not as much information available for testing and sample sizes for aluminum alloys as for steel, which is mainly because of a smaller scale application of aluminum in the automotive industry. It is found that with few exceptions, the overlap of the specimens is the same as the width. [26]

Figure 3-2-1 Specimen dimensions [22]
One can see in Figure 3-3, ANSI/AWS curve was used for sample width determination. The width of the specimen is 25 mm.
One can see that the width is 25 mm when the sheet thickness is 2 mm. The length is 90 mm, but in order to simplify the computation in future work, the length was finally decided 100 mm.

The two aluminum sheets have an overlap whose size is determined in Figure 3-2-4. These references are used for spot welding, as friction-stir riveting is similar to spot welding, we use the above references for friction-stir riveting. After the sizes had been determined, sample materials were prepared.

3.3. Parameters for the tensile test

As mentioned in previous section, the rivets are steel ones, and they were heat treated, and the two sheet metals are aluminum alloy AA 5754.

Based on Dr. Hongyan Zhang’s Assembly and Joining Process lecture notes, the sample dimensions are determined, the dimensions of the sheets used for tensile test will be two 100*25*2 mm aluminum AA 5754 sheets. The rivet will join the sheets and form an overlap. Figure 3-2 shows the dimensions of the specimen.
The tensile shear testing will be conducted. The tensile testing types and conditions will be

(1) Different penetration of depth
2.4 mm, 2.8 mm, 3.2 mm, 3.6 mm, 4.0 mm

(2) Different clamping force
10 foot pound, 20 foot pound, 30 foot pound

(3) Volume of die
Flat die, small die with a volume of 7.33 mm³, large die with a volume of 21.2 mm³.

3.4. Performance of friction-stir riveting

Figure 3-4 shows all the performances of friction-stir riveting joints (volume of die, clamping force).

Figure 3-4- 1 A joint with a flat support
In Figure 3-4-1, one can see the bottom sheet does not have a deformation, so some of the materials were squeezed upwards and got out of the drilled path.

![Figure 3-4-1](image1)

**Figure 3-4-1** A joint with a 7.33 mm³ die

In figure 3-4-2, one can see the squeezed material is less than that in Figure 3-4-1, this is because some of the material flowed into the die cavity.

![Figure 3-4-2](image2)

**Figure 3-4-2** A joint with a 7.33 mm³ die

![Figure 3-4-3](image3)

**Figure 3-4-3** A joint with a 21.2 mm³ die
In figure 3-4-3, one can see the squeezed material is much less than that in Figure 3-4-1 and Figure 3-4-2. Most of the squeezed material went into the large die cavity.

![Image](image1.png)

**Figure 3-4-4 A joint with 10 foot-pound clamping force**

In figure 3-4-4, one can see that the aluminum sheets are not joined together, because 10 foot pound clamping force is not enough to join the sheets together. It is not able to provide sufficient downward force to hold the aluminum sheets. Horizontal movement occurred during the riveting process.
A joint can be created with 20 foot-pound clamping force.

Figure 3-4-6 shows an expected joint. One can hardly see the interface on left side. The aluminum sheets were tightly joined together. It should be a good joint, we will show its tensile test output in the next section.
3.5. Tensile test experiments

Some experiments were conducted to test the quality of friction-stir riveting joints. As mentioned in previous chapters, the quality of a friction-stir riveting joints is related to the interface position and shape, and especially the position of faying interface end. The depth of penetration and the die volume are two important parameters. The rivets penetrate deeper, more material is pushed up, and this forms the interface. An INSTRON 5569 tensile tester was used to operate the experiment. The weld will rotate during the tensile test, as seen in Figure 3-5. Figure 3-5 is actually showing the rotation of a spot welding. Friction-stir riveting has the similar joints to those of spot welding, so we use the figure to show the motion of rotation. When loads are applied on both end of the sheets, sheets begin to bend and rivet begins to rotate. A weld rotation angle will be obtained after the sheets bend. Finally the sheets will separate from each other and the rivet will separate from either sheet or both sheets. The fractured samples are shown in Figure 3-6. The outputs are shown in Figure 3-7.

![Figure 3-5-1 Weld rotation [1]](image-url)
Figure 3-5-2 to Figure 3-5-11 show the fractured states of joints during the experiments.

From Figure 3-5-2, one can see a shallow cavity on the right aluminum sheet, it does not form a joint. The rivet penetrates the top layer and slightly touched the bottom layer, so it can not form a mechanical interlock. When tensile force was applied on the sheets, the sheets separated easily.
Figure 3-5- 3 Fractured joint with penetration of 2.8 mm

From the figure, one can see the cavity is still shallow, some of the material was tore off the sheet by the rivet. It did not form a mechanical interlock. It only has some stirred and mixed zones.
In Figure 3-5-4, one can see a drilled hole on the left sheet. The sheets have some bending.
Figure 3-5-5 Fractured joint with penetration of 3.6 mm

In Figure 3-5-5, one can see the separation of the sheets. The material on the sheet below was totally tore off. The reason will be explained in the future.
Figure 3-5-6 Fractured joint with penetration of 4.0 mm

The depth of penetration is 4.0 mm, the rivet penetrated through the first layer, so a drilled hole was left on the sheet above.

Figure 3-5-7 to Figure 3-5-11 will show the fractured joints with different depths of penetration. The width of the sample is 50 mm.
Figure 3-5- 7 Fractured joint with penetration of 2.4 mm (50 mm width)
Figure 3-5- 8 Fractured joint with penetration of 2.8 mm (50 mm width)
Figure 3-5- 9 Fractured joint with penetration of 3.2 mm (50 mm width)
Figure 3-5- 10 Fractured joint with penetration of 3.6 mm (50 mm width)
Figure 3-5- 11 Fractured joint with penetration of 4.0 mm (50 mm width)
Figure 3-5- 12 Fractured joint with flat support

Figure 3-5- 13 Fractured joint with small die (volume: 7.33 mm³)
Figure 3-5- 14 Fractured joint with large die (volume: 21.2 mm$^3$)

Figure 3-5- 15 Fractured joint with 20 foot pound clamping force
3.6. Failure Analysis

From the previous experiments, we can observe 11 different failure modes. All these types of joints will be discussed below to understand the different characteristics between the failure modes. These joints were formed by different depth of penetration, clamping forces, and die cavity volume. Figure 3-6 shows the outputs of load vs. displacement. Figure 3-6-1 to Figure 3-6-6 show the tensile tests of samples with different depths of penetration, the width of the sample is 25 mm. Figure 3-6-7 to Figure 3-6-12 show the tensile tests of samples with different depths of penetration, the width of the sample is 50 mm.
As shown in Figure 3-6-1, one can see one of the peak loads is only 700N, which is far from sufficient. When it reaches slightly more than 700N, the curve has a sudden drop which means the sheets separated. A weak joint was formed by an insufficient rivet penetration. The depth is 2.4 mm, which is just more than the 2 mm
thick aluminum sheet. The top metal was penetrated through and rivet just slightly touched the bottom metal, as shown in figure 3-6-1; actually, there is no mechanical interlock and solid bonding between the two sheet layers. It breaks easily, and it only has a little stirred and mixed zones between the rivet and the bottom sheet layer. The other curve has the same reasons for fracture, but it shows a better peak load and displacement. The reason why it shows a better result is that the depth of penetration is slightly beyond 2.4 mm due to slightly inaccuracy of the rivet size. Therefore, it has a larger mixed zone, the mixed zone provides a larger load endurance. But it is still far from satisfaction.

**Penetration 2.8 mm**

![Graph showing load vs. displacement](image)

**Figure 3-6-2 Load vs. displacement of a joint with penetration of 2.8 mm**
By increasing the depth of penetration, we can get stronger joints. As one can see in Figure 3-6-2, it shows joints formed with a penetration of 2.8 mm. It does not have a mechanical interlock either. The red curve shows a peak load of 3000N, which is preferable, but the displacement is not satisfactory. The blue curve reaches 3500N. When the displacement is only around 0.5 mm, the red curve drops suddenly. It has a small bounce which is caused by the stirred and mixed zones. Part of the stirred and mixed zones separate and the rest part is still connected, but it only last for a short time. After a short while, the rivet separated from the sheet. The weld was ruined. The blue curve has the same reasons for fracture. One can see the deformed sample from Figure 3-5-3.
When the depth of penetration goes to 3.2 mm, one can see in Figure 3-6-3, the red curve shows a peak load of a new high level of 3600N. The replicate output (blue curve) reaches almost the same level. The blue curve drops to 2400N which is caused by the break of solid state bonding of the material. When the displacement goes from 1mm to 2.7mm, the load stays above 2000N. This is because of the interlocking of the
rivet. The curve suddenly drops after the displacement reaches about 2.8 mm, and it is because the rivet rotated and partly separated from the sheet metal, but the rivet was partly hooked on the edge of the sheets, so the joint can still bear some load. One can easily judge that the quality of the joint is much better than previous two. The red curve has the same reason for fracture. The fracture sample can be seen in Figure 3-5-4.

Figure 3-6-4 Load vs. displacement of a joint with penetration of 3.6 mm
As seen in Figure 3-6-4, it is an output of fracture joints with penetration of 3.6 mm, the blue curve’s peak load is about 3000N, and the curve does not appear as smooth as the previous joint with a penetration of 3.2 mm. It appears like waves, and this is because of the position changing of the rivet. Some part of the rivet separated from the sheet, and other parts bear the load until it completely separated from the sheet. This is shown in Figure 3-6-4. The displacement can reach 4 mm. The joint with a penetration of 3.6 mm has a good quality. The red curve even shows a better performance.
When the depth comes to 4.0 mm, two aluminum sheets were penetrated through. The peak load is not too bad, but the joint broke as the displacement was only 1.2 mm. As we can see in Figure 3-4-11, the rivet head is located just on the interface, so it does not have a sufficient interlock or mechanical bonding. It only has some stirred
and mixed zones between the rivet and the material. Only a little materials left under the rivet head. It breaks easily. The joint with penetration of 4.0 mm is too weak.

Comparisons were made to show the results of replicates. Figure 3-6-6 shows two comparisons of two different replicates, each of the replicates was conducted independently.
From the comparison of different depth of penetration, one can see the strongest joints are the ones with penetration depth of 3.2 mm and 3.6 mm. They are both joints of good quality, as they have both large peak load and great displacement. They can bear more force.

Some more tensile tests were operated, this time, the dimension of the sample were not changed except for the width. The width of the samples were changed from 25mm to 50mm. The figures below will show the results of these tensile tests.
From Figure 3-6-7 one can see that the peak load of the blue curve is about 2700 N, the curve drops after it reaches the highest point, then it shows a smooth slope until it reaches the horizontal axis. The peak load of the red curve is about 2200 N. The curve suddenly drops to about 800 N after it reaches the highest point. The reason why it suddenly drops is that the stirred and mixed zones partly fractured and the rest part bears some more load for a little while, so one can see the curve lasts for a longer displacement. It took a few seconds for the rivet to separates from the aluminum sheets. The peak loads of these two curves are not as high as expected.
Figure 3-6-8 Load vs. displacement of a joint with penetration of 2.8 mm

Figure 3-6-8 shows two different curves of joints with penetration of 2.8 mm. The peak load of these two curves are both approximately 4000 N. Firstly, we analyse the blue curve, it drops to the bottom after it reaches the highest point. This phenomenon indicates that the rivet totally separates from the sheets. The sample only has some stirred and mixed zones, it does not have mechanical interlock. The stirred and mixed zones fractured after it reached the peak load. The red curve shows a longer displacement. It has a sudden drop after it reaches the highest point, because part of the stirred and mixed zones fractures and the rest part still connected. It lasts for a little while and finally totally fractured.
From Figure 3-6-9 one can see that the peak load of the red curve is about 4400 N, but it has a sudden drop, the curve goes a little higher after the sudden drop. It is because the rivet rotates and partly separates from the sheets, the rest part of the rivet still hooked on the edge of the drilled hole. So it bears more load and lasts a little while until the rivet totally separates from the sheets. The blue curve does not have a higher peak load, but it shows a larger displacement than the red curve. The displacement reaches about 4 mm. The curve drops obviously when the displacement reaches about 3 mm. It stays smoothly before the displacement reaches 3 mm. The blue curve shows a better quality of the joint than the red one. The results are better than the samples with a width of 25mm. The reason is that the wider a sample is the harder it will bend. So the tensile shear strength is the main factor which can bear more load. The rivet is also hard to rotate, so mechanical interlock can bear more load than the samples with a width of 25mm.
From Figure 3-6-10 one can find out that both the curves have large peak loads. The peak load of the blue curve is about 5000 N. These two curves also show a large displacement, both of them have a large displacement beyond 4 mm.

Figure 3-6- 11 Load vs. displacement of a joint with penetration of 4.0 mm

Figure 3-6-11 shows the tensile test results of the joints formed with a penetration of 4.0 mm. In this case, the rivet’s bottom flange reaches a depth of 4 mm. Two aluminum sheets have a total thickness of 4.0 mm, it means the rivets nearly
penetrate through the aluminum sheets. One can see from Figure 2-14 (e), the joint does not have a mechanical interlock which helps to hold the aluminum sheets. It only has some stirred and mixed zones, the only strength comes from the stirred and mixed zones. Only a little materials left under the rivet head. The sheets are hard to bend, so tensile shear strength is the main factor to bear the load, the mixed zone is hard to be torn off.

![Penetration](image1)

![Penetration 2](image2)

Figure 3-6-12 Comparison of joints with different depth of penetration
Figure 3-6-12 shows the comparison of different joints formed with different depths of penetration. One can easily figure out that joints with a penetration of 3.6 mm are the best among these joints, for they simultaneously have a large peak load and a large displacement.

**Penetration 2.4 mm**

**Penetration 2.8 mm**
Figure 3-6 13 Tensile tests outputs of samples with width 25mm and 50mm
In Figure 3-6-13, one can see that most of the dotted lines show a better load endurance and displacement than solid lines. The dash lines have larger peakload and displacement, because widths of the samples are 50 mm, tensile shear strength is the main factor which provide a better load endurance, the 50 mm wide aluminum sheets are more difficult to bend than 25 mm aluminum sheets, the rivets in 50 mm aluminum sheets are more difficult to rotate, therefore, the shear strength is the main force which makes the aluminum sheets separate from each other. The mechanical interlock formed by the rivets and aluminum sheets can provide a good load endurance. When tensile shear strength is applied to the aluminum sheets, the sheets are still hold together tightly until the material ruptured or the sheets bend, rivets rotated and finally separated from the aluminum sheets.

The output curves of clamping force are shown in Figure 3-6-14 and Figure 3-6-15. A tensile test for a joint with 10 foot-pound clamping force was not conducted, for it did not form a joint as seen in Figure 3-4-4.
Figure 3-6- 14 Load vs. displacement of a joint with 20 foot-pound clamping force

The peak load reaches about 3000N. The solid state bonding is not that strong. The curve has a slope, and this is because the rivet rotates as the increment of displacement. As seen in Figure 3-6-7.
The peak load is 3300N, and the curve drops slowly with the increase of displacement. It stays above 1500N for a long time then it drops to x axis. The displacement reaches about 3.7 mm. Application of 30 foot-pound clamping force made the two sheet metals move close and tightly to each other. The rivet can create a better interlock and solid state bonding with the material of the aluminum sheets.
A comparison is made in Figure 3-6-16. We can easily tell which one is better. The one with a 30 foot-pound clamping force is better. The clamping force relates to the tightness of two sheet metals. Three experiments were conducted. As shown in Figure 3-3-4, sample with 10 foot-pound clamping force cannot form a joint. Because the clamping force is not sufficient, the sheet metals are not able to get close to each other. Horizontal movements occurred during the riveting process. In other words, they separated when the rivet was going into them. The joint with a 30 foot-pound clamping force can bear a larger load than that with a 20 foot-pound clamping force.
Figure 3-6- 17 Load vs. displacement of a joint with a flat support

A joint formed with a flat support is not durable. Although its peak load reaches 3000N, the curve drops when the displacement reaches about 0.6 mm. It is the moment the solid state bonding disappears. Then, the interlock bears the load. When the displacement reaches about 2 mm, the curve suddenly drops, and the slope indicates that the rivet rotates and gradually separates from the sheet metals. The interfaces of the sample curl up, it is not desirable.
A joint formed with a small die has a peak load of 3300N. The curve shown in Figure 3-6-18 shows the peak load. After it reaches the peak load, the curve drops suddenly, and it drops to 2400N, and then it rises to about 2700N. When the displacement reaches 3 mm, the rivet separated from the sheets. The interfaces also curl up but less than that with a flat support.

A joint with a large die cavity appears strong. It has a peak load of 3500N, and the curve drops when it reaches the peak load. This means that the rivet begins to rotate; part of the rivet separates from the sheet; then the mechanical interlock bears
the load until the rivet completely separates from the sheets. It has a displacement of 7 mm. The sample interfaces are approximately horizontal which is desirable. It also has the largest stirred and mixed zones among these three samples.

Figure 3-6-20 Previous load vs. displacement of a joint with a large die (volume: 21.2 mm³)

Figure 3-6-20 shows a previous experiment output of a joint with a large die cavity. Every parameters were strictly controlled, one can see the curve appears smoothly and the load stays high above 2200N for a long time. The curve stops when the displacement reaches about 2.8 mm. As the experiment control was set as “stop testing when the load drops 50 percent”, the curve stops. But we can infer that the quality of a joint with a large die cavity is strong. Because after the first drop, the curve rises and reaches more than 3000N, and then the curve stays stable.

<table>
<thead>
<tr>
<th>Specimen</th>
<th>Final thickness (mm)</th>
<th>Final length (mm)</th>
<th>Final width (mm)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>2.00000</td>
<td>100.00000</td>
<td>25.00000</td>
</tr>
</tbody>
</table>
Figure 3-6-21 Comparison of joints formed with different die cavities

As shown in Figure 3-6-21, a joint formed with a large die cavity appears to be strong, and the peak load is about 4000N.

From Figure 3-6-17 to 3-6-21, a joint formed with a large die appears to be the best of the three. It has a peak load of 3500 N. As seen in Figure 3-6-21, one can easily tell the results. A joint formed with a large die cavity gives the best performance. The interlock and solid bonding are both strong when a large die is used.

From all the figures above, the major results of the failure modes observed in these friction-stir riveted joints can be concluded as followings:

1. Joints formed with penetration of 3.2 mm and 3.6 mm can be accepted, and all other joints are too weak to bear the load. The rivets should penetrate neither too deep nor too shallow in order to form a good mechanical interlocking and solid bonding around the rivet.
2. From the figures we can analyze that the samples have two steps of deformation before rupture. The first step is a material stretching stage, in which the sheet around the rivet is first stretched; meanwhile, the crack begins from the interface end where the force gathered. The second step is a tearing stage, in which the rivet rotated, and it tore the sheets apart. As seen in the figures, each of the plots shows a sudden drop after it reached the peak load. After that, it slightly increased in load bearing, that is the second step.

3. A good joint is greatly affected by adequate penetration, different volumes of die, and different clamping force.

4. Some observations in this study:

   (1) Some rivets stays on the sheet when the layers broke. Mostly, it is caused by insufficient penetration. It has a very weak joint because the rivet can hardly touch the bottom sheet, a mechanical interlocking can not be formed.

   (2) The rivets separated from the sheets with rotations. In this situation, large load can be observed from the figures.

   Figure 3-6 shows the load vs. displacement curves during tensile testing. All the curves show that each of them has an increase in load at the beginning of the testing; then, after reaching the peak load, the load decreases with additional displacement. A friction-stir riveted joint can be strong with large displacement. Therefore, displacement can be used to describe the ductility of a friction-stir riveted joint. The total displacement when the specimen finally fails will be used to describe the friction-stir riveted joints. A related quantity is the energy absorbed by the sample. It can be calculated by the area under the load vs. displacement curve and, therefore, it may also serve as an indicator of the bearing capacity of a friction-stir riveted joint.
The peak load, together with the displacement or the energy, should fully describe a friction-stir riveted joint’s strength.

### 3.7. Failure mode analysis

A lot of experiments were operated and three failure mode were observed. The performance of a joint is greatly related to the failure mode. Therefore, some typical failure modes were identified to be a means of direct visual inspection of joint quality. Five different types of joints shown below will tell the differences between the failure modes. These different joints were made by a variety of combinations of the depth of penetration, die sizes, and clamping force.

A weak joint was made by insufficient rivet penetration. The depth of the rivet penetration is 2.4 mm, which is far from sufficient. The rivet penetrates the first layer and the rivet head just slightly touched the top of the second layer, as shown in Figure 3-7-1(a). It does not form an mechanical interlock between the first and second aluminum sheets. The joint breaks easily, only certain solid bonding exists between the rivet and the bottom layer. The corresponding load vs. displacement plot is shown in Figure 3-7-1(b) whose peak load is less than 800 N.

![Figure 3-7-1](image-url)  
**Figure 3-7-1** Tested sample (a) and the corresponding mechanical response (b) for a joint with 2.4 mm rivet penetration
Increasing the depth of rivet penetration can create stronger joints. Figure 3-7-2(a) shows a sample with 2.8 mm penetration. Although the depth is still not sufficient, a significant improvement in the load bearing capacity can be seen. The rivet stays on the second layer.

![Image](2.8mm.png)

(a) ![Graph](graph2.png)

(b) 

Figure 3-7-2 Tested sample (a) and the corresponding mechanical response (b) for a joint with 2.8 mm rivet penetration

Increase the depth of penetration to 3.6 mm which proved to be an appropriate depth. The peak load becomes higher than previous ones. It reaches almost 4000 N and the displacement becomes larger. The tested sample can be seen in Figure 3-7-3 (a), one can see the significant sheet deformation. The rivet stays on the second layer.

The corresponding mechanical response can be seen in Figure 3-7-3 (b)

![Image](3.6mm.png)

(a) ![Graph](graph3.png)

(b) 

Figure 3-7-3 Tested sample (a) and the corresponding mechanical response (b) for a joint with 3.6 mm rivet penetration
The joints become stronger when depth increases. However, a further increase in penetration may result in unwanted output. When the depth of penetration increases to 4.0 mm as shown in Figure 3-7-4, the peak load drops. This is because the attachment of the top sheet to the joint decreases. There is very little aluminum sheet material left under the rivet head. Therefore, the joint link is weakened.

![Image](40_mm.png)

(a) (b)

**Figure 3-7-4** Tested sample (a) and the corresponding mechanical response (b) for a joint with 4.0 mm rivet penetration

The failure modes observed can be summarized in the followings:

(1) Except for the one with 4.0 mm rivet penetration, all the other joints have similar curves at the beginning of the test. The one with 4.0 mm rivet penetration has a smaller peak load and slope as a result of less deformation of the first layer.

(2) The deformation of the samples usually contain 2 stages. In the first stage, the aluminum material around the rivet is stretched, cracks begin to initiate from the end of the interface. The second stage contains tearing caused by the rotation of rivet. One can easily see each of the force vs. displacement curves has a sudden drop after it reaches the peak load, which is the end of the first stage; after that the load bearing capacity increased, which is the second stage.
(3) A good joint should have a proper depth of rivet penetration and small interface curl up. Die sizes and clamping can improve the quality of a rivet joint in this aspect.

Three major failure modes are observed in this research:

(1) The first kind of failure mode is when the rivets stays on the top layer after the joint is destroyed, frequently caused by insufficient depth of rivet penetration. It does not form a joint or the joint is just formed by a little attachment of the first sheet and the second sheet.

(2) The second failure mode is when the sheets separate from each other and the rivet stays on the bottom sheet. The peak load in this kind of failure mode shows a better value than that in the first failure modes. When the rivet is separated from both the sheets with significant rotation, a larger joint strength is usually associated with this kind of failure mode observation.

(3) The third failure mode is when the sheets separate from each other, the rivet stays on the bottom layer without rotation. This observation is caused by excessive depth of rivet penetration. The joint strength is usually unwanted.

3.8. Some information from defined parameters

Some parameters were defined in Section 2, as seen in Figure 2-2. Figure 3-8-1 shows the dt of different die types. We can see that the value of dt increases as the volume of die increases.
Figure 3-8-1 dt vs. die type

Figure 3-8-2 db vs. die type

Figure 3-8-2 shows the relationship of db and die types.

The values of db decrease as the die sizes increase.

Figure 3-8-3 to Figure 3-8-4 show the relationships of dt and different depth of penetration.

Figure 3-8-3 dt vs. penetration

As the penetration increases, the value of dt decreases because the rivet goes deeper, and the end of interface gets closer to the upper rivet head.
Figure 3-8-4 db vs. penetration

Figure 3-8-4 shows the db values of different penetrations. The values of db increase as the feed depth increase.

Figure 3-8-5 and Figure 3-8-6 show the different tensile test outputs of different values of dt and db.

Figure 3-8-5 Peak load vs. values of db

One can see that when the value of db reach about 2.2 mm, the peak loads show good values. Only one db value above 2.2 mm shows a 1500 N output, it is because
the riveting process did not provide a sufficient mixed zone, and it is also an output of a 2.8 mm penetration sample.

Figure 3-8- 6 Peak load vs. values of $dt$

One can see that when $dt$ values range from 0.2 mm to 1.4 mm, the peak loads show good values.
Chapter 4

4. Summary and future work

4.1. Summary

(1) After studying the friction-stir riveting process, interface curl, mixed zone, depth of penetration, and volumes of dies, different clamping force are considered to be important factors that may affect the quality of riveted joints significantly.

(2) Experiments show a good quality performance of joints with flat interface.

(3) The depth of penetration should be 3.2 mm~ 3.6 mm.

(4) The volume of the die should be 7.33 mm³.

(5) The clamping force should be at least 30 foot-pound.

4.2. Future work

(1) Simulations should be conducted to compare the real results with simulation results.

(2) Some other parameters should be considered, and some related experiments should be done, such as the material of the driver, different joining material, clamping positions, etc.

(3) Application of friction-stir riveting for automobile industry.

(4) The stability of the experiment process should be well controlled.
(5) Several experiments will be repeated to verify the results which were given in this thesis.

(6) Rivet size will be redesigned to provide better experiment results.
References


P.M. Thornton et al, 1996


