

A Thesis

entitled

Friction-Stir Riveting: an Innovative Process for Joining Difficult-to-Weld Materials

by

Samuel J. Durbin

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

Dr. Hongyan Zhang, Advisor, Committee Chair

Dr. Ahalapitiya Jayatissa, Co-advisor, Committee
Member

Dr. Sarit Bhaduri, Committee Member

Dr. Patricia R. Komuniecki, Dean
College of Graduate Studies

The University of Toledo

May 2012

Copyright 2012, Samuel J. Durbin

This document is copyrighted material. Under copyright law, no parts of this document may be reproduced without the expressed permission of the author.

An Abstract of
Friction-Stir Riveting: an Innovative Process for Joining Difficult-to-Weld Materials

by
Samuel J. Durbin

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

The University of Toledo
May 2011

Aluminum and magnesium alloys are expected to make considerable contributions in reducing the weight of automobiles as they are increasingly used as an alternative to steel; improving fuel economy and vehicle performance while simultaneously reducing emissions. Before the wide-scale adoption of aluminum and magnesium alloys in the construction of automobiles can take place, the difficulties of joining these materials must be overcome. Two areas with promise include self-piercing riveting, in which a rivet is driven into sheet metal, without predrilling a hole; and friction-stir welding, in which a rotating tool is fed along the seam of the materials to be joined, mixing the materials without melting them to form a joint. Both of these processes avoid melting the material to be joined therefore not causing the undesirable changes in the metallurgical properties associated with resistance spot welding.

Friction-stir riveting combines both friction-stir welding and self-piercing riveting. The process involves driving a spinning rivet into sheet metal without predrilling a pilot hole. A joint formed by this process has the benefits of a mechanical fastener similar to self-piercing riveting, and of a material mixture zone similar to friction-stir welding;

without suffering from the undesirable changes in mechanical properties associated with more conventional welding techniques.

This work presents the basics of tooling design, a fundamental understanding of the friction-stir riveting process, and the feasibility of joining difficult-to-weld materials using this technique.

Acknowledgements

I would like to thank my advisor Dr. Hongyan Zhang and co-advisor Dr. Ahalapitiya Jayatissa whose leadership and support over the past two years made this research possible. I would also like to thank my co-researchers Genze Ma and Weiling Wang for the great teamwork. I must also express my appreciation to Mr. John Jaegly, Mr. Tim Grivanow and Mr. Randall Reihing of the University of Toledo MIME machine shop, for their patience when asked to do the impossible, and the help they provided in solving problems as they arose. Financial support provided by the National Science Foundation and The University of Toledo was also greatly appreciated.

Table of Contents

Acknowledgements.....	v
Table of Contents.....	vi
Objective.....	viii
List of Figures.....	ix
1 Introduction.....	1
2 Friction-Stir Riveting Tool Design.....	8
2.1 Rivet Design.....	8
2.2 Clamp design	22
2.3 Driver design.....	34
3 Friction-stir Riveting Process	40
3.1 Material flow, and interface geometry at different depths of penetration	41
4 Friction-Stir Riveting Process Characterization.....	46
4.1 Effect of die on interface geometry	46
4.2 Metallographic Analysis of the riveted joint microstructure	52
4.3 Joining of various materials	55
4.4 Element mapping with electron scanning microscope.....	61
5 Conclusion	65

5.1 Summary	65
5.2 Future work	65
References.....	69
List of Publications	71

Objective

The goal of this thesis and of the associated research is to conduct a proof-of-concept of the proposed friction-stir riveting process; to study the structure of these joints and understand their influence on joint quality; and to conduct mechanical and metallurgical testing to relate joint attributes to joint strength.

List of Figures

1-1 A self-piercing riveted joint	3
1-2 Flawed self-piercing rivet joint	4
1-3. Friction-stir welding	5
1-4 Friction stir rivet	6
1-5 Cross section of friction stir riveted joint	7
2-1 Friction-stir riveted joint with critical dimensions labeled	8
2-2 Rivet geometry nomenclatures	9
2-3 First generation rivet design (1)	10
2-4 First generation rivet design (2)	10
2-5 Second generation design (1)	11
2-6 Second generation rivet design (2)	12
2-7 Simplest conceivable rivet design	13
2-8 Rivet design with 4-mm diameter bottom flange	14
2-9 Rivet design with 5-mm diameter bottom flange	15
2-10 Damaged rivet bottom flange	15
2-11 Rivet design similar to Figure 2.9 except with reinforced bottom flange	16
2-12 Rivet design with 6-mm bottom flange	17

2-13 Specimen with fractured rivet	18
2-14 Similar to Figure 2.12, but with a sharper tip	19
2-15 Rivet design similar to Figure 2.14 but with 4-mm rivet stem	20
2-16 Final rivet design used in research	21
2-17 Rivet ready for insertion, with insufficient clamping	23
2-18 Cross section of riveted joint with severe sheet separation	24
2-19 Second generation clamp technique	25
2-20 Riveted joint sample with minor sheet separation	25
2-21 Third generation clamping technique (overall view)	27
2-22 Third generation clamp with stress concentrating washer	27
2-23 Third generation clamp; top view	28
2-24 Third generation clamp; bottom view	28
2-25 Third generation clamp; side view; washer visible at center on bottom	28
2-26 Riveted joint, with slight sheet separation to right of rivet	30
2-27 Riveted specimen, without sheet separation	30
2-28 Fourth generation clamp technique	32
2-29 Fourth generation clamp top view	32
2-30 Fourth generation clamp in use	33
2-31 Fourth generation clamp bottom view, with welded washer	33
2-32 Fourth generation clamp side view	34
2-33 Driver with matching rivet	36

2-34 Phillips driver	36
2-35 Rivet with desired Phillips driver slot	37
2-36 Final rivet design with diver slot	37
3-1a Inserted 2.5 mm	42
3-1b Inserted 2.7 mm	42
3-1c Inserted 2.8 mm	42
3-1d Inserted 3.0 mm	42
3-1e Inserted 3.3 mm	43
3-1f Inserted 3.6 mm	43
3-2 Orientation of bisecting a riveted joint	45
3-3 Cross sectional view of riveted joint cut without offset sectioning	45
4-1 Typical friction stir riveted joint	47
4-2 Joint samples without die	49
4-3 Joint samples with small die	49
4-4 Joint samples with large die	49
4-5 Small and large dies	50
4-6 Riveting procedure setup with a die	51
4-7 Over etched specimen of an Al joint	52
4-8 Under etched sample	53
4-9 Various etchings	54-55
4-10 Typical riveted aluminum joint	55

4-11 Microscopic view of aluminum joint	56
4-12 Two sheets of magnesium alloy riveted together	57
4-13 Microscopic view of magnesium sample	57
4-14 Composite joint macro view	58
4-15 Composite joint micro view	59
4-16 Composite joint, macro view	60
4-17 Composite joint, microscopic view	60
4-18 Section of rivet to undergo element mapping	61
4-19 Image from electron scanning microscope	62
4-20 Iron	63
4-21 Carbon	63
4-22 Manganese	63
4-23 Chromium	63
4-24 Nickel	64
4-25 Silicon	64
4-26 Magnesium	64
4-27 Zinc	64
4-28 Oxygen	64
4-29 Aluminum	64
4-30 Potential rivet for further research	66
4-31 Rivet sample with partial void visible	67

4-32 Potential location of rolling bearings

68

1 Introduction

Resistance spot welding has proven to be a versatile method for the joining of steels, being used extensively in the automotive industry and other industries. As the automotive industry progresses to using more aluminum alloys and magnesium alloys in order to reduce vehicle weight to improve performance and economy, while also reducing emissions, alternative joining methods will be required. Resistance spot welding of aluminum alloys and magnesium alloys are possible, but create complications making it impractical for the large scale automated use required by the automotive industry. For example the lower electrical resistance of both aluminum and magnesium alloys requires higher electric current during resistance spot welding in order to generate the necessary heat, which in turn leads to shorter electrode life. Two alternative joining methods that show promise for the joining of materials that are difficult for resistance spot welding are self-piercing riveting, and friction stir welding.

Self-piercing riveting is an attractive alternative to resistance spot welding for difficult-to-weld metals, or dissimilar metals. The repeatability of self-piercing riveting along with the low cost of joint formation makes it ideal for the automotive industry [1]. The process of self-piercing riveting involves applying a compressive load onto the two sheets of material that are to be riveted together, then driving a semi-tubular rivet through the upper layer and into the bottom layer. A die cavity is placed underneath the material

to be riveted, as the rivet is being driven into the material, the material fills the cavity, and the shape of the cavity forces the rivet to flare outward, causing the layers of material to be anchored together by the rivet as seen in Figure 1-1. Figure 1-1 illustrates the cross section of a self-piercing rivet joint, the steel rivet appears black, the upper layer is a 2 mm thick sheet of aluminum, and the bottom layer is a 1.4 mm thick layer of steel. The steel appears black in the photo as a result of polishing, since steel polishes to a finer finish than aluminum. When light is reflected off the polished aluminum it is scattered, making it convenient to photograph; when light is reflected off the polished steel it does not scatter as much as with aluminum. Instead of scattering, the reflected light as is the case with aluminum, the steel experiences specular reflection, where light coming from a single direction will reflect off a mirror-like surface with a single outgoing direction. Due to the specular reflection, the steel appears black, as no light from the steel reaches the camera. One can see how the rivet completely passes through the upper layer of aluminum and enters the lower layer of steel, without penetrating through the lower layer of steel. The 'w' shape of this specimen is a result of the die that is placed underneath the sheet metal during the riveting process. The shape of the die causes the rivet to flare out during riveting helping to form a strong joint.



Figure 1-1. A self-piercing riveted joint

Self-piercing riveting has the advantage of being able to conveniently join dissimilar metals as in Figure 1-1. A self-piercing riveted joint can be made inexpensively and in large quantities with high level of consistency making it ideally suited for the automotive industry. There are limitations to self-piercing riveting, for example when riveting sheets of magnesium alloys, the brittleness of magnesium alloys (with comparison to aluminum alloys) can cause fractures to occur where the stress is concentrated as the rivet is being driven into the sheets of magnesium alloys as seen in figure 1-2. Figure 1-2 reveals where a fracture has occurred during the riveting process.

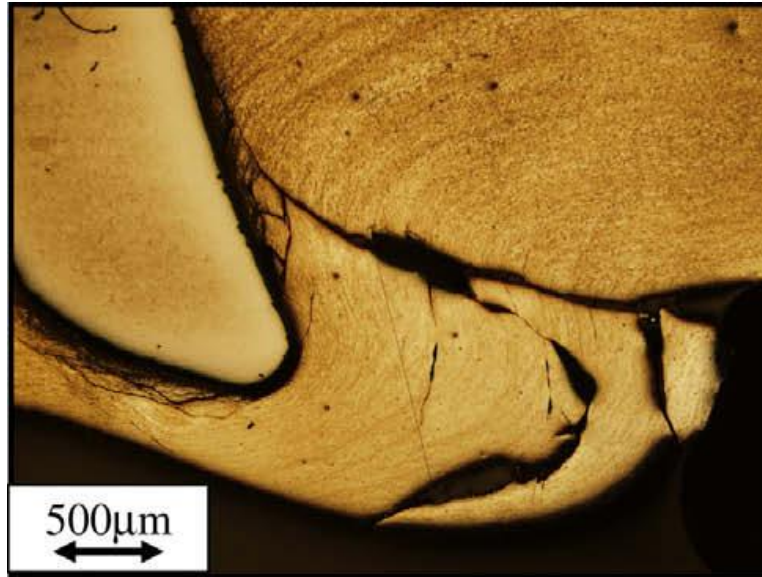


Figure 1-2. Flawed self-piercing rivet joint [2]

Friction stir welding is another area of interest for the joining of difficult to weld materials. To form a square butt joint using friction stir welding, a cylindrical tool is fed, rotating, along the interface between the two pieces of material to be joined. The rotating tool uses friction to heat the material to be welded together to the point of becoming plastic without heating the material all the way to its melting point. As the tool is fed along the interface, the material in front of the tool is softened from the heat, and then is pushed around and behind the tool, filling the void that would have been created as the tool passes. Figure 1-3 depicts a rotating tool advancing up the joint line of the two pieces to be joined. The tool has a probe that penetrates the material, as well as a shoulder to apply a downward force on the material; the friction of the rotating shoulder heats the material before the material comes into contact with the probe.

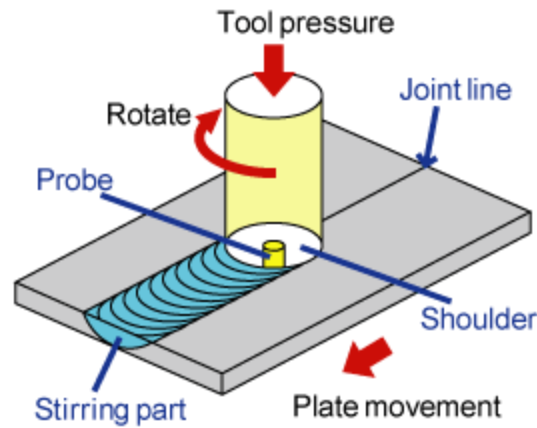


Figure 1-3. Friction stir welding [3]

Friction stir welding has the advantage of being a solid state joining process, meaning that the material is never heated to the liquid state, as in more traditional welding techniques, such as arc welding. Since the material is not heated to such extremes, the material does not go through undesirable metallurgical changes, associated with more conventional welding techniques, negating the need for heat treatment after the welding is complete.

Friction stir riveting is a cross between self-piercing riveting and friction stir welding. A rivet, as shown in Figure 1-4, is spun and driven into multiple layers of sheet metal. As in friction stir welding, the heat generated by friction softens the metal to a plastic state, without completely melting it, allowing it to deform without fracturing. Similar to self-piercing riveting, no predrilled pilot hole is necessary, reducing the time and cost per joint, and a mechanical fastener is left in place to provide strength. Figure 1-4 shows three different views of the identical friction-stir rivet: on the left is a top view revealing a plus sign that allows the driver to spin the rivets as it is pushing the rivet into sheet metal; the middle rivet reveals the profile of the rivet; the rivet on the right is a bottom view of the rivet. As the rivet is being driven into the sheet metal, the softened material fills the empty space surrounding the rivet stem, as seen in Figure 1-5.



Figure 1-4. Friction stir rivet

Figure 1-5 presents the cross section of a friction stir riveted joint, again the rivet (which is made of steel) appears black due to the specular reflection. The joint in Figure 1-5 joins sheets of aluminum that are both 2 mm thick. To the left of the rivet one can see the interface between the two layers of aluminum. A die was used below the two layers of aluminum during the riveting process to allow some of the material replaced by the rivet to flow downward, causing the bump at the center on the bottom of this specimen. This thesis describes the experiences and results as the feasibility of friction stir riveting was explored.

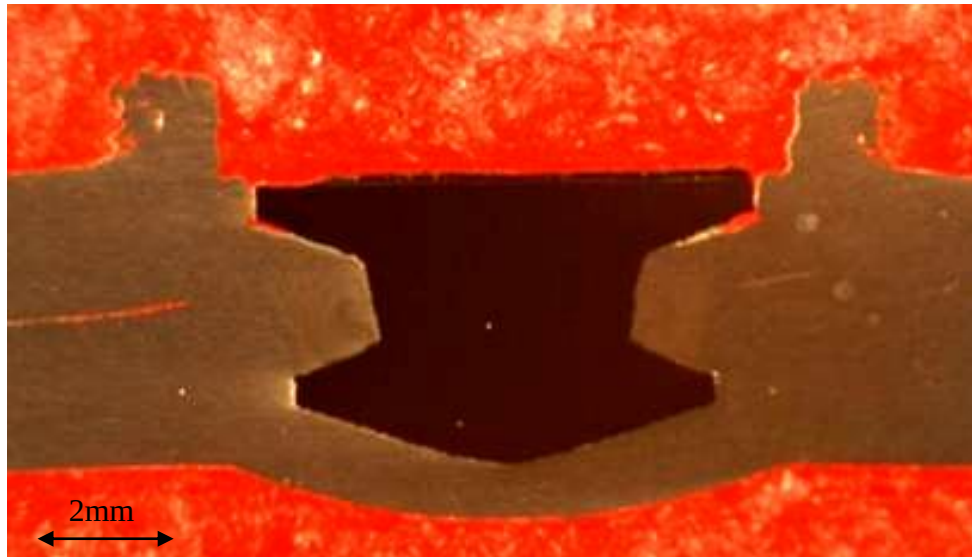


Figure 1-5. Cross section of friction stir riveted joint

2 Friction-Stir Riveting Tool Design

2.1 Rivet Design

To produce the most robust friction stir riveted joints possible, rivets were designed to produce the largest stirred and mixed zone (W in Figure 2-1) possible, and a large interlock (L). These characteristics, mixed zone, and mechanical interlocking, along with solid bonding provide the riveted joint with its strength. For this research attention was restricted to studying the effects of the mixed zone and interlocking area.

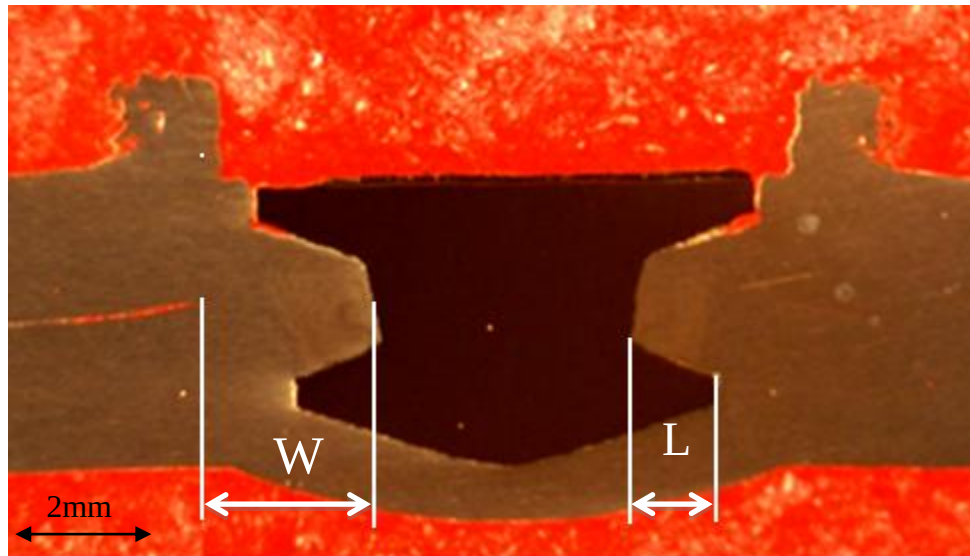


Figure 2-1. Friction-stir riveted joint with critical dimensions labeled

The nomenclature used to describe the different parts of the rivet can be seen in Figure 2-2. The bottom portion of the rivet will be called rivet bottom flange; the central portion of the rivet, the rivet trunk; and the top portion of the rivet, the rivet head.

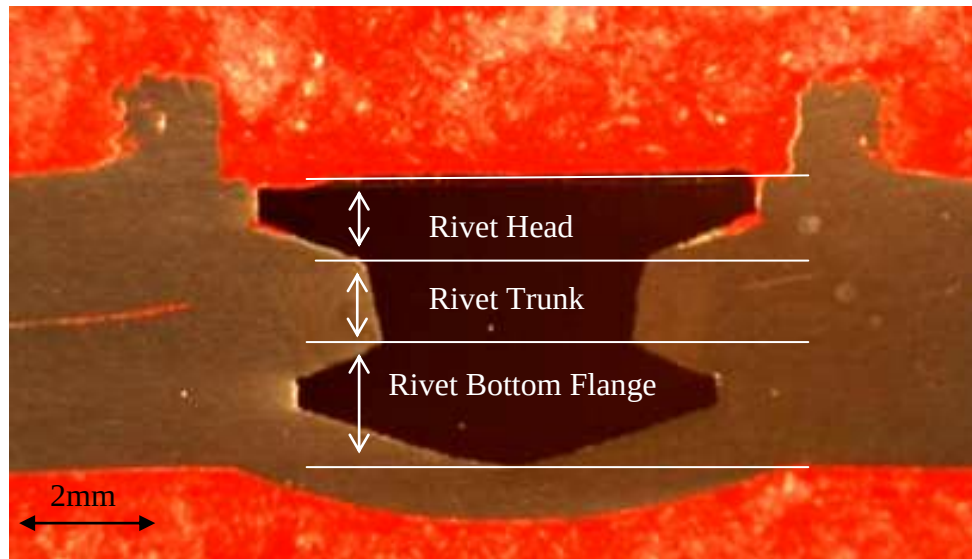


Figure 2-2 Rivet geometry nomenclatures

The two original friction stir rivet designs, Figures 2-3 and 2-4, featured a concave rivet head. The logic behind this design is that as the rivet was penetrating the softened sheet metal, the concave shape of the rivet head would help to redirect the displaced material back towards the central rivet stem, filling in any potential void. This design turned out to be impractical, machining this rivet on a lathe, be it a CNC or manual is all but impossible. In order to machine the concave shape of the rivet head, the cutting tool would be required to be approximately 1 mm in diameter, which would lead to unreasonable short cutting tool life. After consulting multiple machine shops it was decided to abandon this design, and come up with a new simpler rivet design.

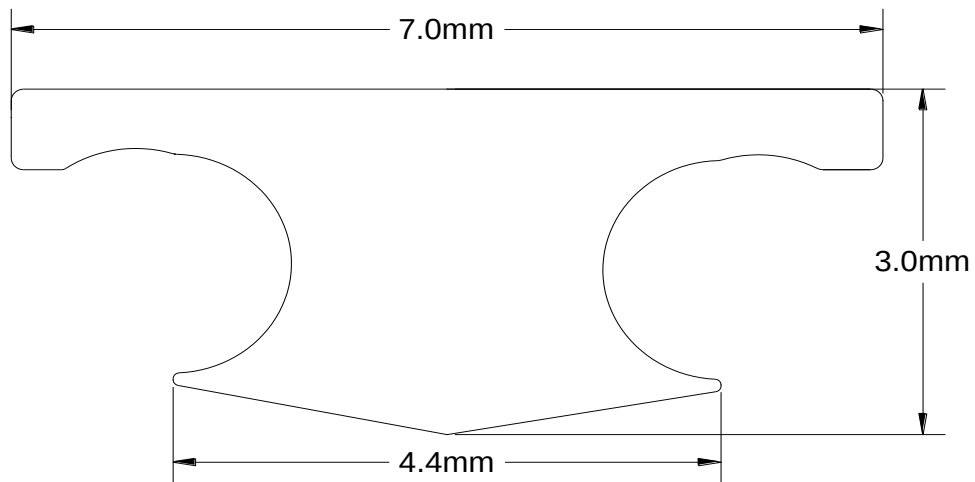


Figure 2-3. First generation rivet design (1)

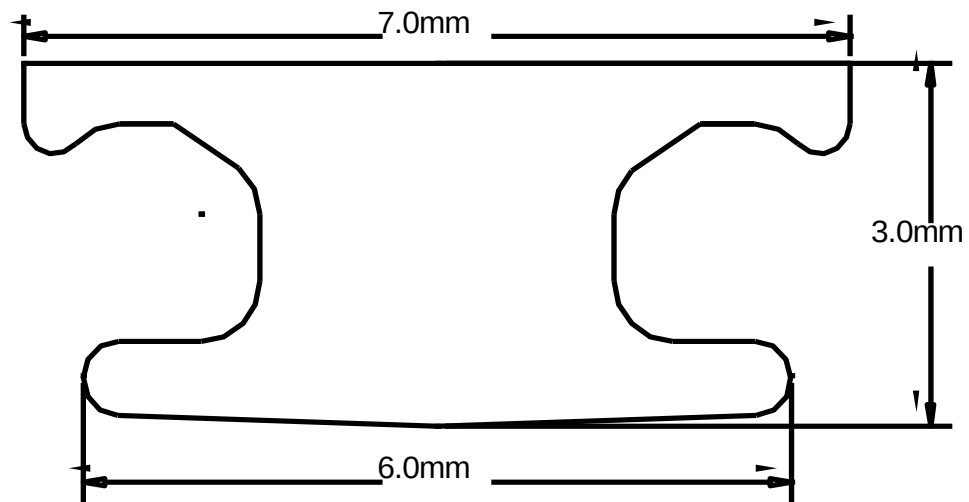


Figure 2-4. First generation rivet design (2)

Two second generation rivet designs seen in Figures 2-5 and 2-6, appeared to be more manufacturable; it was decided to proceed with the design in Figure 2-5. This design also proved to be unsuccessful, due to the small 2.5-mm diameter of the rivet

stem. As the rivet was being spun and driven into the sheet metal the rivet head would break off at the stem, due to the torque being applied from the spinning motion. It was concluded that a rivet stem diameter of 2.5 mm was insufficient.

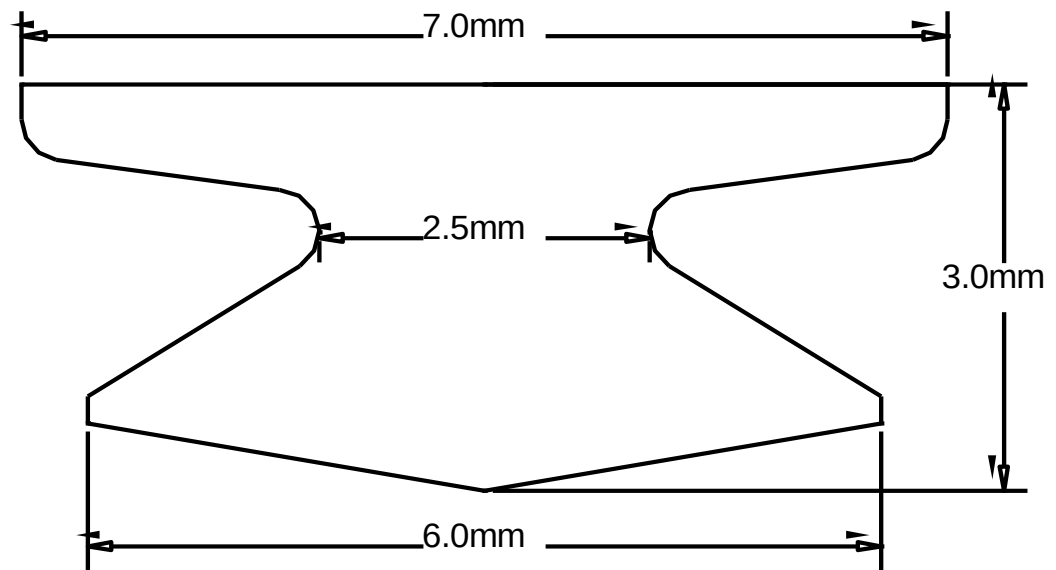


Figure 2-5. Second generation design (1)

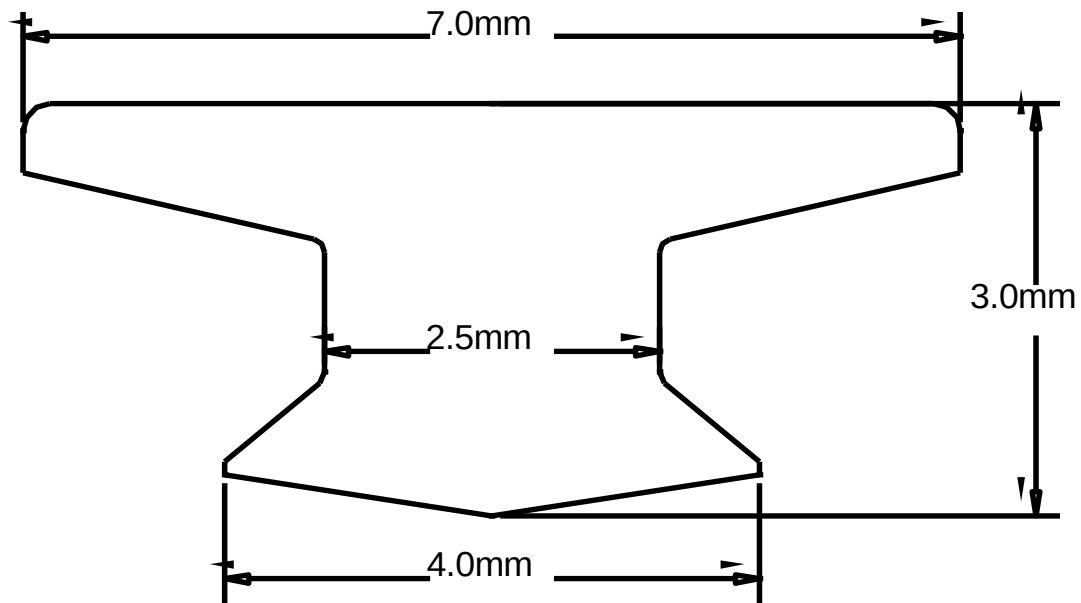


Figure 2-6. Second generation rivet design (2)

After months without progress, it was decided to take a step back, and focus the rivet design with manufacturability, and ease of insertion in mind. The rivet design in Figure 2-7 does not have a bottom flange as in all previous and subsequent rivet designs. The lack of bottom flange offers the advantage of ease of insertion during the riveting process, and the disadvantage of producing a weak joint. This rivet design was more about having a foundation upon which to build, as opposed to forming very strong joints. Using this rivet design the first successful joints were formed, while the complications with driving the rivet, and in clamping down the sheet metal could be focused on.

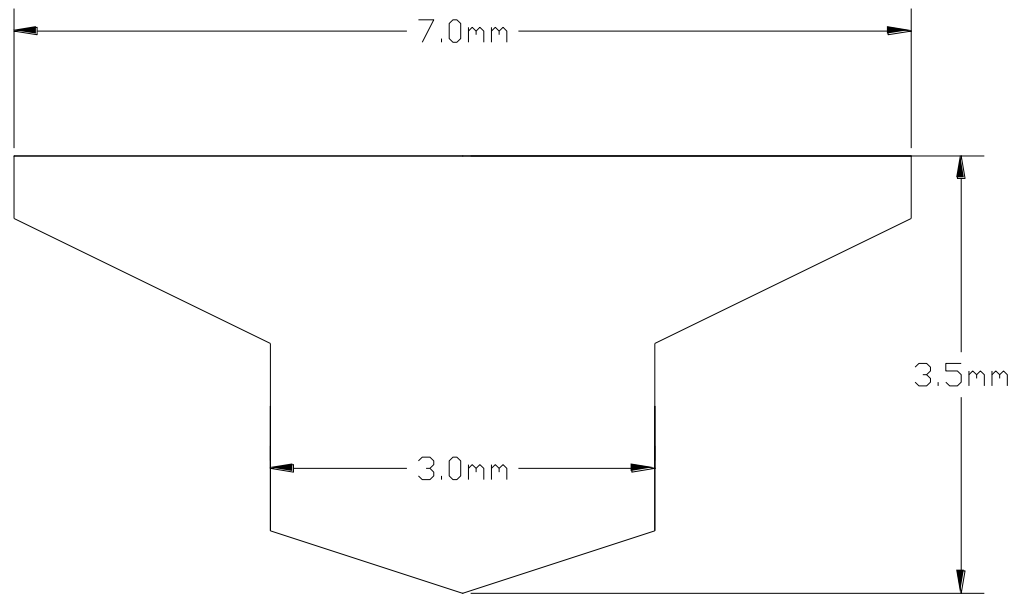


Figure 2-7. Simplest conceivable rivet design

After the success experienced with the rivet in Figure 2-7, a rivet that would produce a stronger joint was desired. Figure 2-8 presents the next rivet design, this one similar to the design in Figure 2-7 except the new design features a 4 mm diameter lower flange, to increase the degree of interlocking and therefore, the strength of the joint.

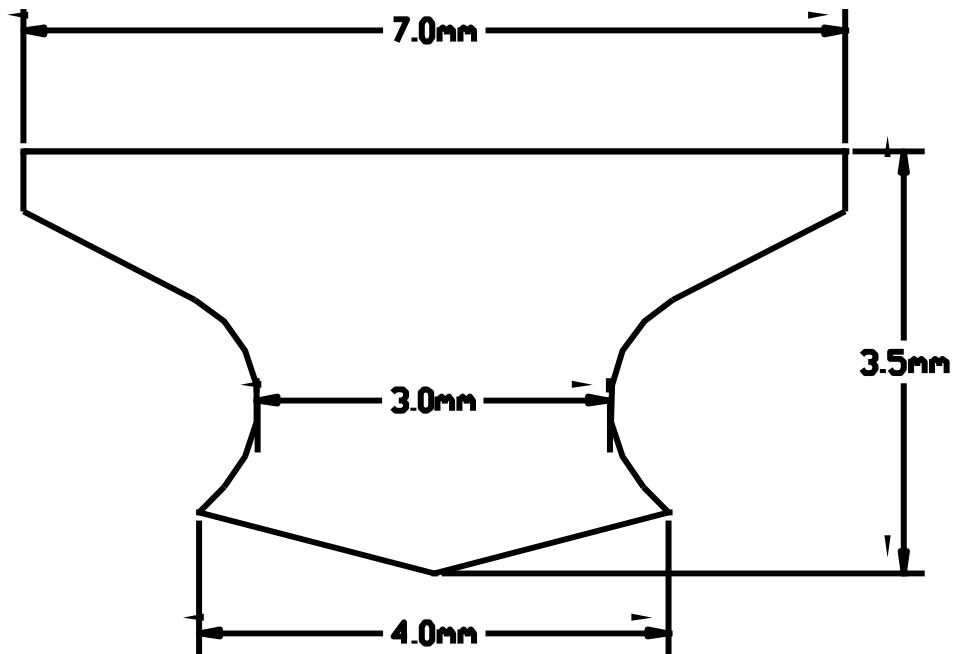


Figure 2-8. Rivet design with 4-mm diameter bottom flange

Knowing that the riveted joint strength would improve from having a larger bottom flange, the design in Figure 2-9 was conceived. This design was similar to the designs in Figures 2-7 and 2-8 except for having a 5-mm diameter bottom flange. When this rivet design was successfully inserted into the sheet metal, it was assumed that the best friction stir riveting joint had just been constructed. Upon closer examination the cross section revealed that the bottom flange curled up during insertion, from the load applied upon the bottom flange by the sheet metal as it was being driven into the sheet metal, as seen in Figure 2-10. In addition, there are unfilled voids near the rivet trunk as seen in the figure.

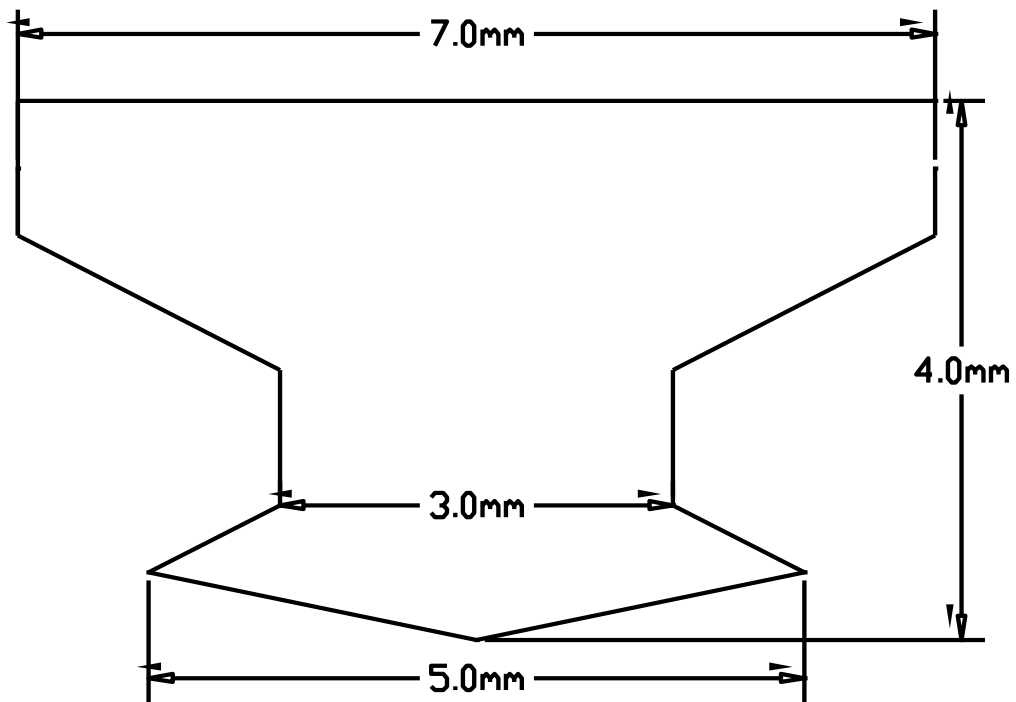


Figure 2-9. Rivet design with 5-mm diameter bottom flange



Figure 2-10. Damaged rivet bottom flange

To combat the problem seen with the design in Figure 2-10 without reducing the diameter of the bottom flange, it was decided to increase the thickness of the bottom

flange, to give the flange the strength that was required to withstand the stresses encountered during the riveting process. This new design is illustrated in Figure 2-11. This design worked with a high level reliability, and produced strong and consistent joints.

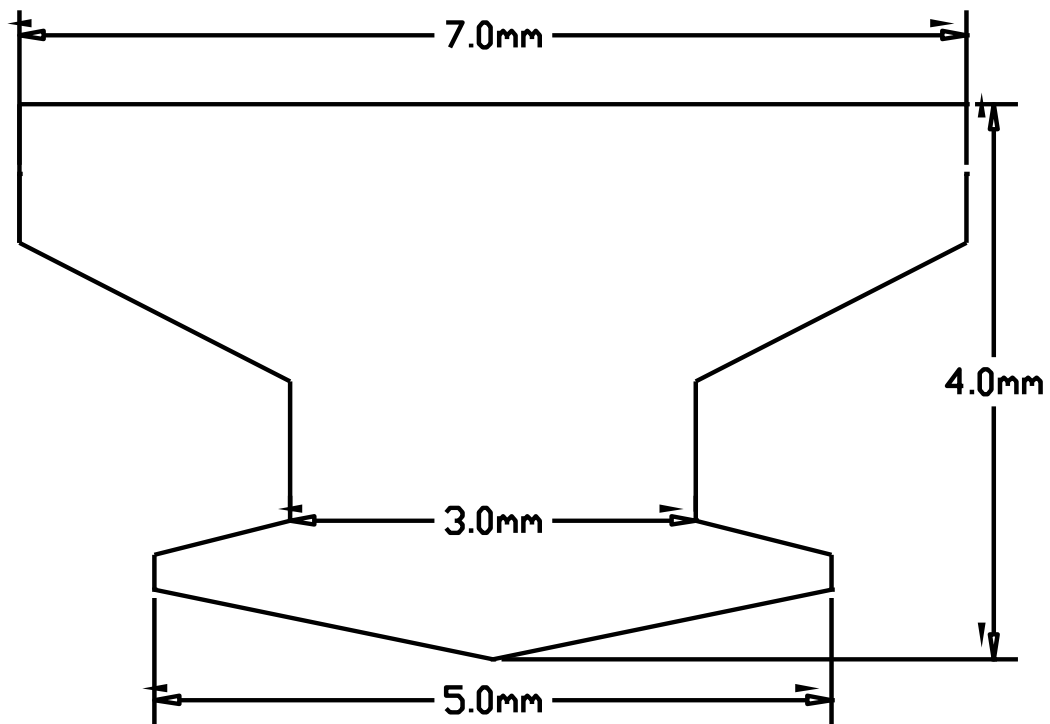


Figure 2-11 Rivet design similar to Figure 2-9 except with reinforced bottom flange

The rivet in Figure 2-11 performed well, but it was assumed that if a rivet with a 6-mm bottom flange could be successfully inserted into the sheet metal, the joint would be of a higher quality. So the rivet design in Figure 2-12 was produced. This design produced mixed results; sometimes the rivet would survive insertion successfully, but other times the rivet would fracture at the rivet stem during insertion, as can be seen in

Figure 2-13. A variety of spindle speeds and feed rates were attempted to find a more reliable process, but without success.

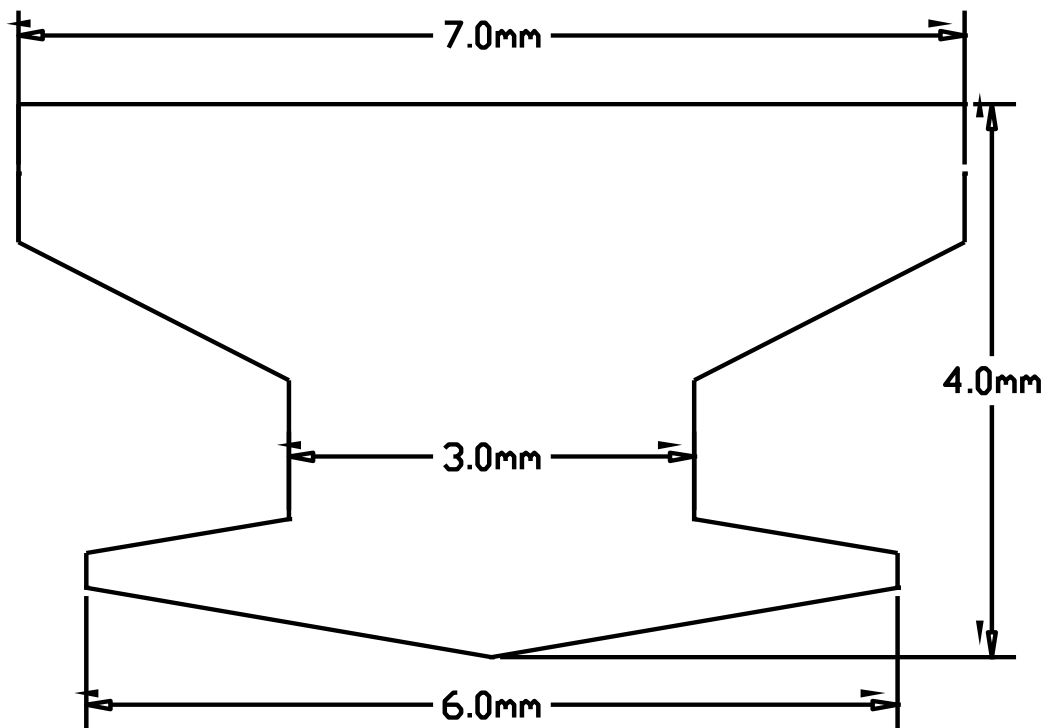


Figure 2-12. Rivet design with 6-mm bottom flange

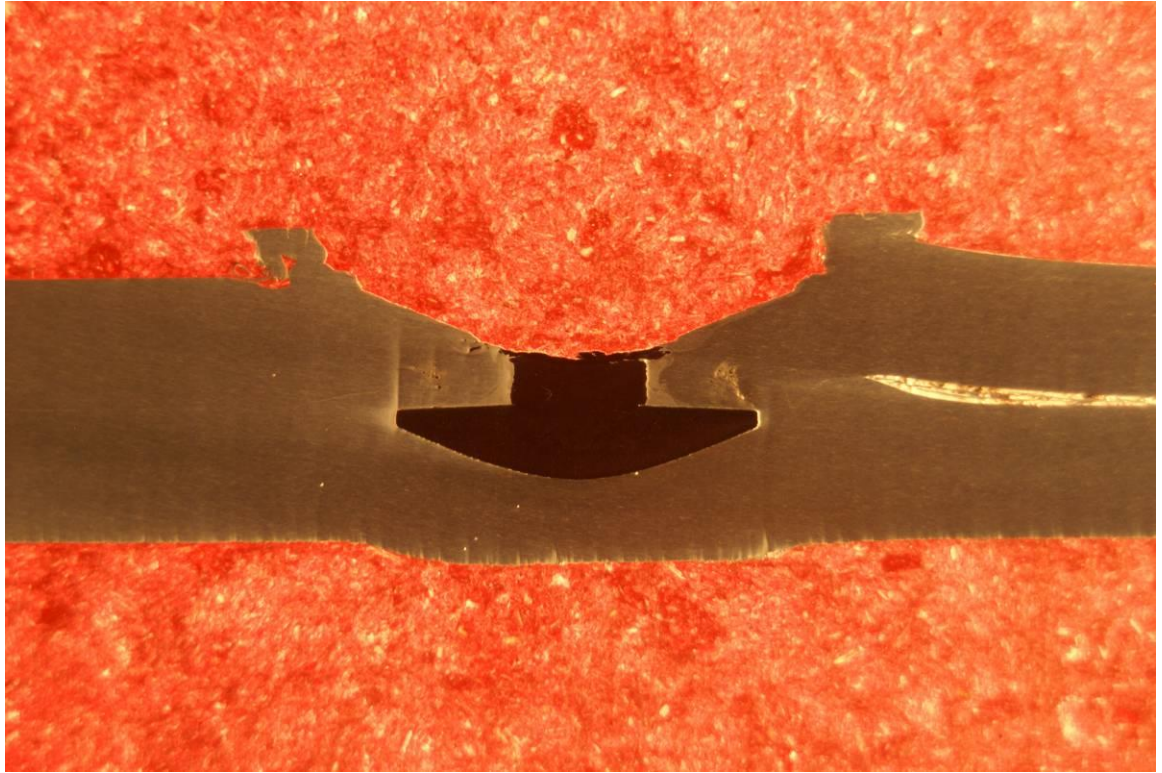


Figure 2-13. Specimen with fractured rivet

Disappointed by the failure of design 2-12, but not wanting to compromise with the 6-mm bottom flange, another rivet with a 6-mm bottom flange was designed, as seen in Figure 2-14. This design featured a sharper tip, to concentrate the heating affect from friction, and reduce loading applied during insertion. This design proved to be no more reliable than the design in Figure 2-12; the rivet would still occasionally fracture at the stem during insertion.

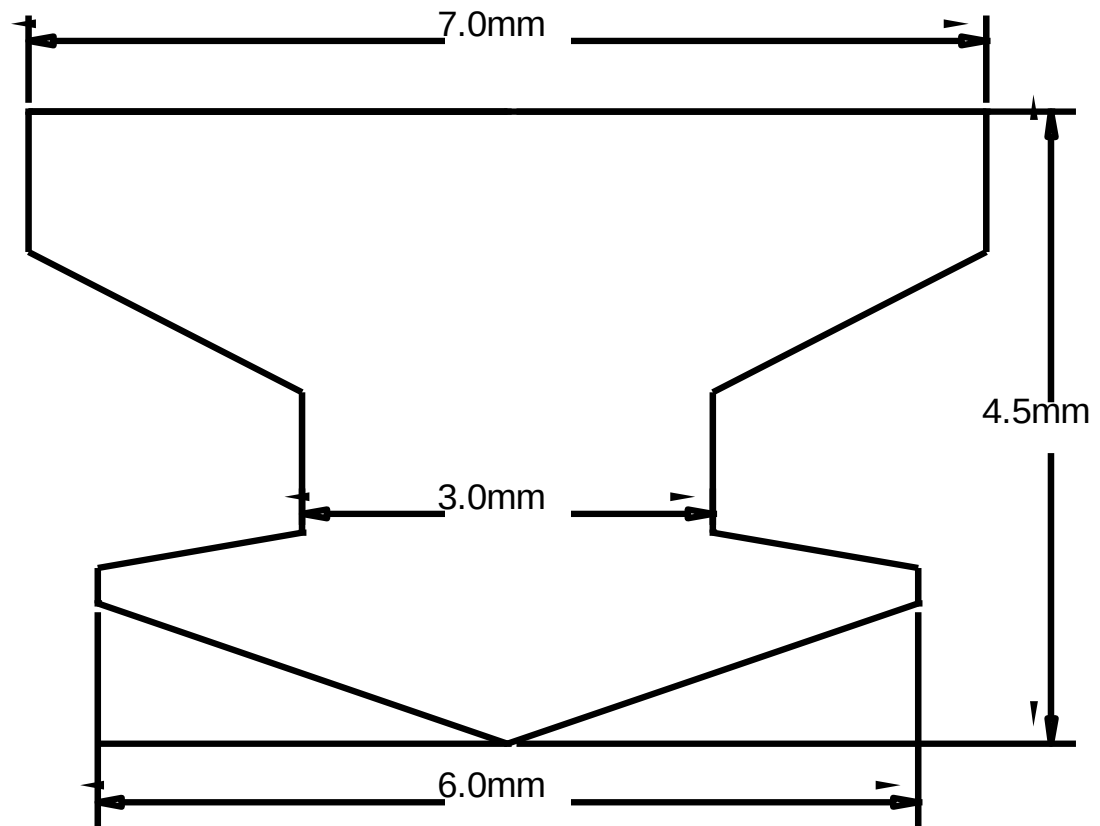


Figure 2-14 Similar to Figure 2-12, but with a sharper tip

Unable to improve upon the consistency of the rivet design of Figure 2-12 or 2-14, heat treatment after machining was conducted. It was also decided to strengthen the weak point of the rivet, by increasing the diameter of the rivet stem from 3 to 4 mm as seen in Figure 2-15. The rivet design in Figure 2-15 is primarily the same as in Figure 2-14 except with an increased diameter rivet stem to 4 mm. This rivet design performed well, producing a sound joint, and being able to handle the stresses applied during the riveting process.

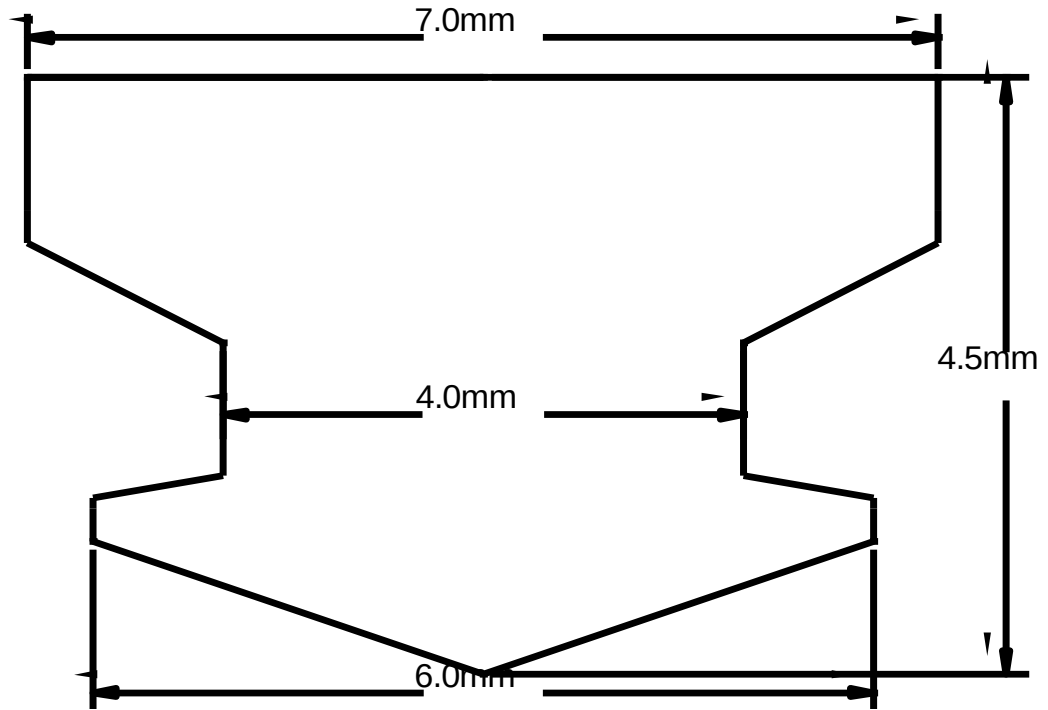


Figure 2-15. Rivet design similar to Figure 2-14 but with 4-mm rivet stem

While the performance of the rivet design in Figure 2.15 was of the highest quality, the design evolved into Figure 2-16 with a stem that converges starting at the rivet head with a wider diameter, then slims to a narrower diameter at the bottom flange. This new design also features a slimmed down rivet head, and is overall shortened by 0.5mm. The tip of the rivet is less pointed than the design in Figure 2-15; there were no observed variations in performance relating to the minor changes that were made upon the angle of the tip of the rivet.

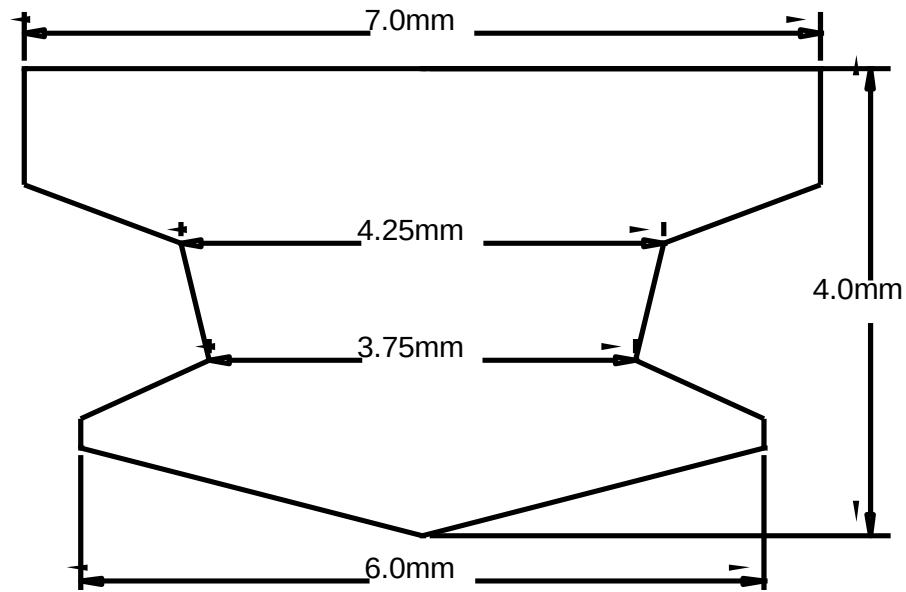


Figure 2-16. Final rivet design used in research

The rivet design in Figure 2-16 performed flawlessly, always producing a solid joint without suffering damage caused during the riveting process, as seen with some of the earlier rivet designs. Additional research might continue to explore rivet design. Perhaps a bottom flange with a larger diameter than 6 mm, or a rivet head diameter larger than 7 mm would improve performance.

As mentioned previously, all rivets were heat treated in order to avoid the problems seen in figure 2-13, where rivets broke at the stem due to the torsional stress. The process used for heat treatment is as follows.

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.

2.2 Clamp design

When the first successful riveted joints started being produced, it was assumed that the downward force being applied to the rivet by the driver, and hence the downward force being applied to the two layers of sheet metal by the rivet, would be sufficient to hold the sheet metal down, during the riveting process. The sheet metal was then clamped in a manner to prevent horizontal travel as seen in Figure 2-17. Figure 2-17 shows a rivet in the center of the frame, with the driver holding the rivet ready for insertion; in the foreground the front jaw of the vice is visible (out of focus), and the background shows the rear jaw of the vice. This clamping technique immediately proved insufficient. Figure 2-18 shows the cross section of an early specimen made under such a clamping technique.

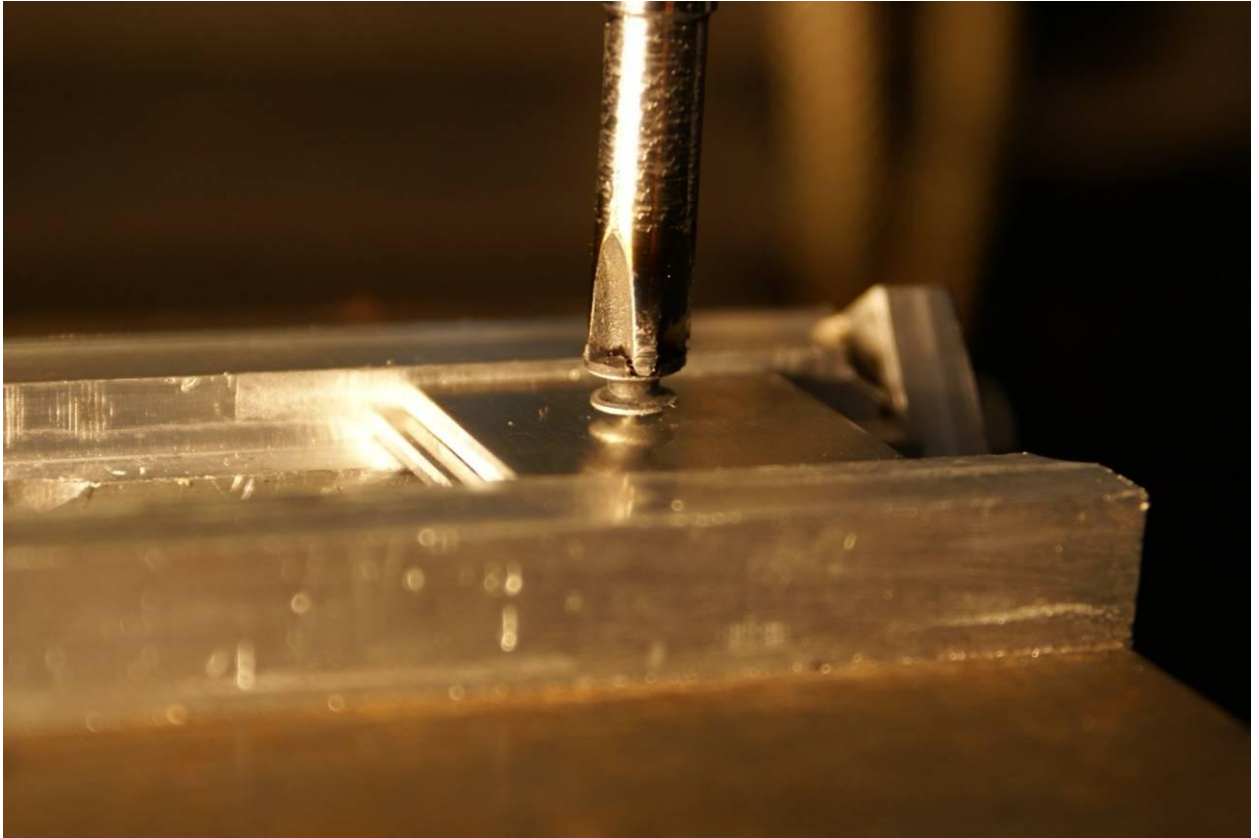


Figure 2.17. Rivet ready for insertion, with insufficient clamping

This clamping technique immediately proved insufficient as can be seen in Figure 2-18. Figure 2-18 displays the cross section of an early specimen taken using the setup seen in Figure 2-17. As can be seen in Figure 2-18 the top layer of aluminum is separated from the bottom layer as the material displaced by the rivet, flows in-between the two layers of sheet metal.

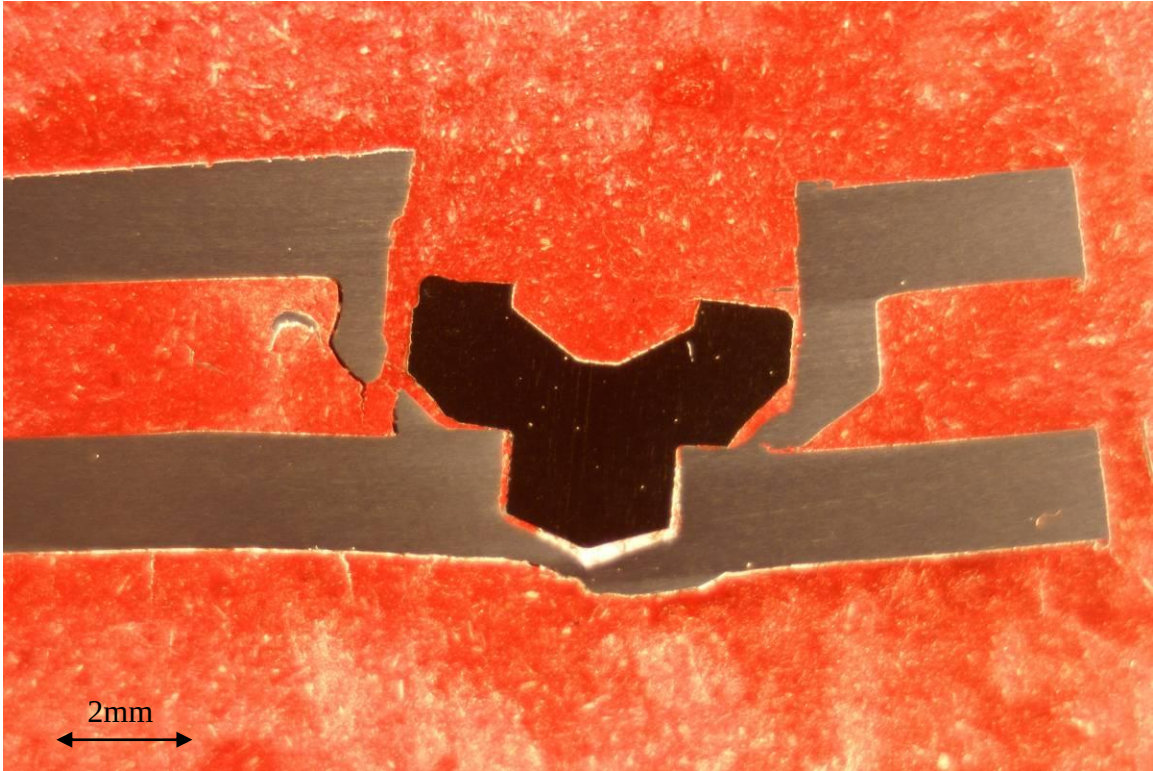


Figure 2-18. Cross section of riveted joint with severe sheet separation

It was soon realized that a downward force would need to be applied during the riveting process. A clamp was applied as seen in Figure 2-19, applying a strong downward force to the upper layer of aluminum, to prevent the separation seen in Figure 2-18. This technique was a vast improvement over the previous technique, but still allowed for some minor separation as seen in Figure 2-20. Figure 2-20 shows a riveted joint taken using the clamping technique shown in Figure 2-19; it should be noted that a large ‘C’ shaped piece with tails is visible to the left of the rivet in this sample; this ‘C’ is merely a plastic clamp used as an aid for metallographic specimen preparation and has nothing to do with the quality of the riveted joint. The separation seen between the two layers of aluminum was deemed unacceptable, even though it represented a vast improvement from the sample presented in Figure 2-18.

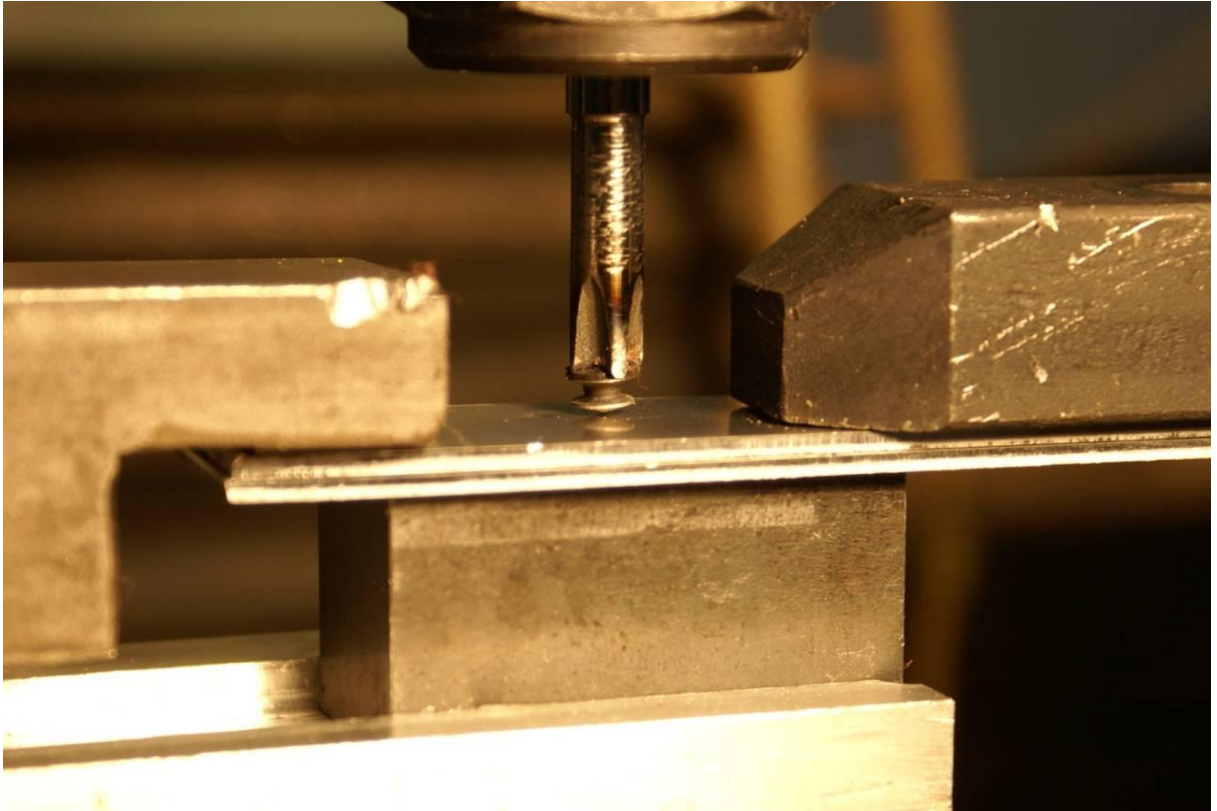


Figure 2-19. Second generation clamp technique

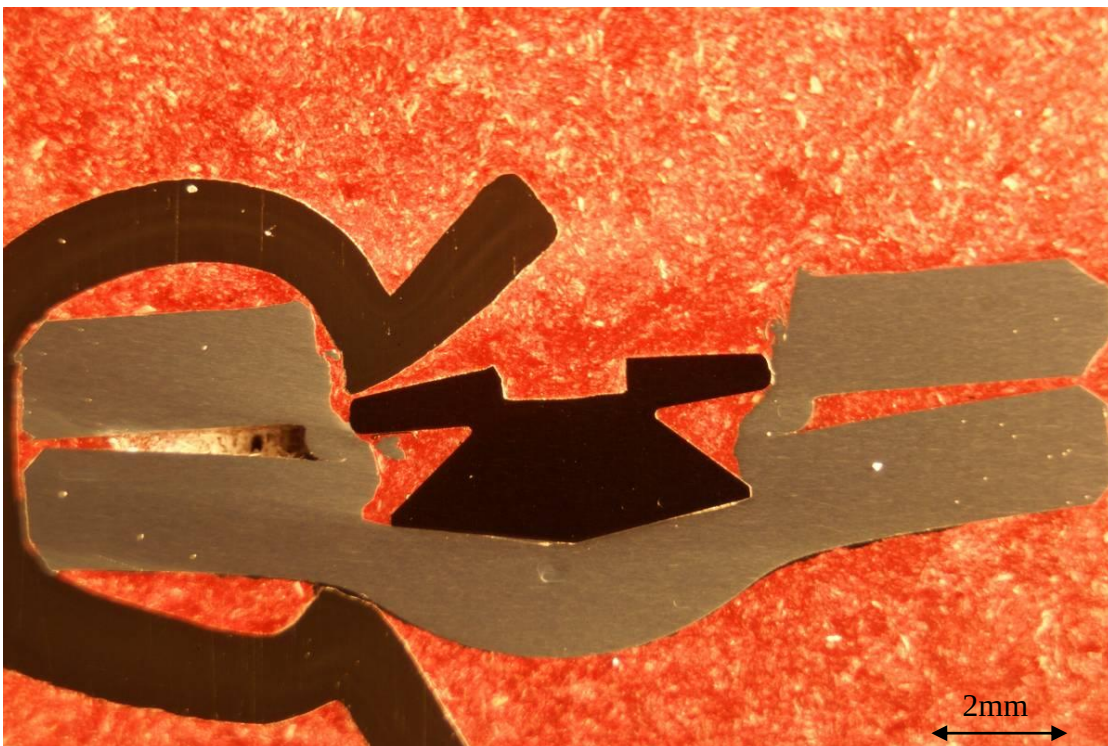


Figure 2-20. Riveted joint sample with minor sheet separation

Figure 2-21 shows the third generation of clamping technique which employed a steel plate clamped tightly to the sheets to apply a downward force evenly to the sheet metal. The goal of this technique was to apply a compressive load to the sheet metal immediately surrounding the rivet to prevent the separation seen in Figure 2-20. When applying a compressive load to the steel plate, the plate would bow under the loading and the resulting loading would be applied to the sheet metal away from the rivet due to the concave down shape of the steel plate under loading. The resulting samples using this technique were of no better quality than those seen in Figure 2-20.

To correct this problem a steel washer was welded to the bottom of the plate. The steel plate and washer were then cut open from the side so they could be easily placed around the rivet and driver while the rivet and driver were in place, for convenience. This clamping setup is as portrayed in Figure 2-21. Figures 2-22 through 2-25 show the clamping mechanism in greater detail, and Figures 2-24 and 2-25 show the washer that was welded to the bottom of the clamp. The washer was welded to the clamp to concentrate the loading applied to the sheet metal, around the rivet, to further reduce the chances of separation during the riveting process.

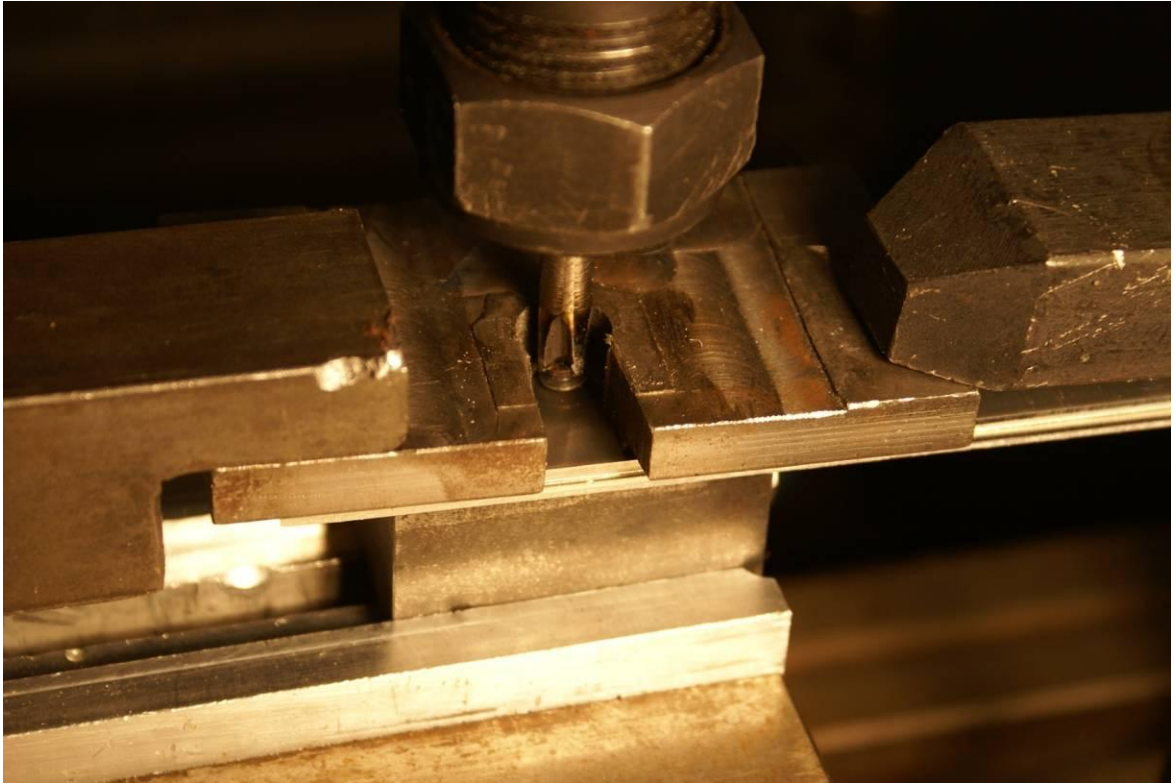


Figure 2-21. Third generation clamping technique (overall view)

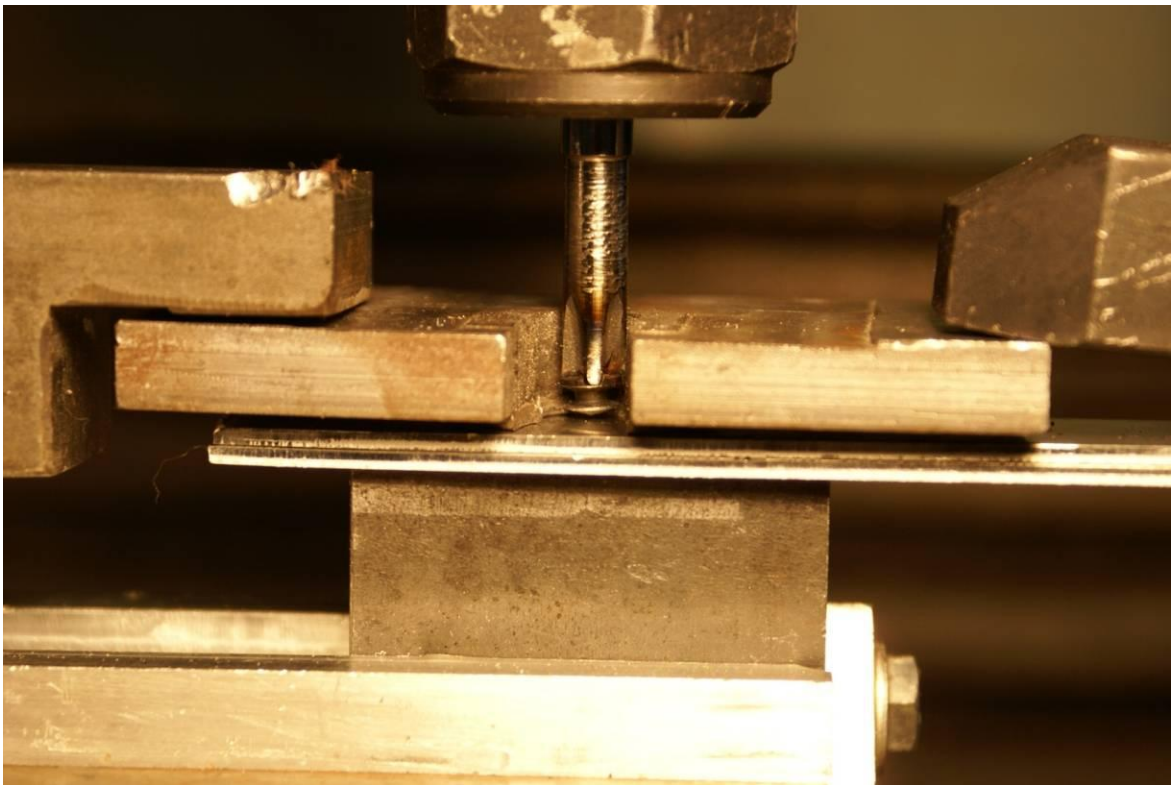


Figure 2-22. Third generation clamp with stress concentrating washer

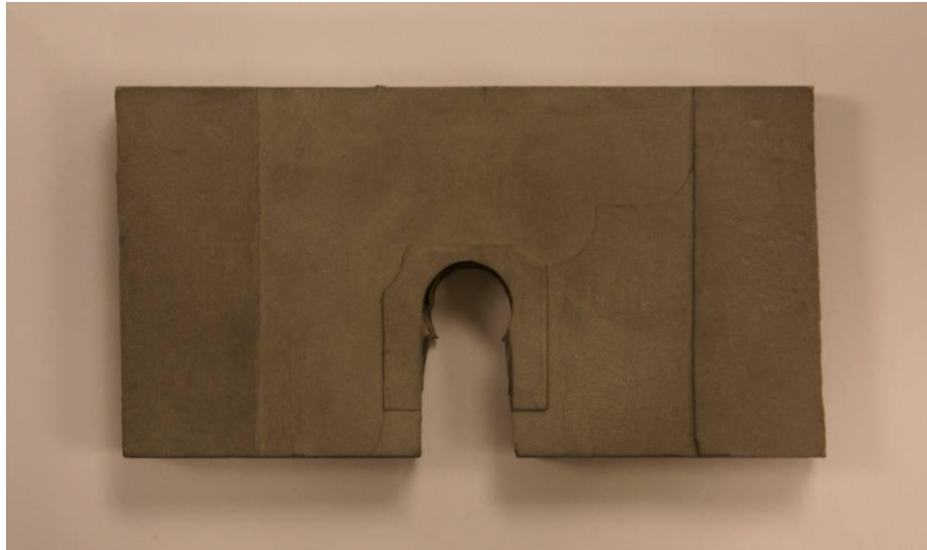


Figure 2-23 Third generation clamp; top view



Figure 2-24 Third generation clamp; bottom view



Figure 2-25 Third generation clamp; side view; washer visible at center on bottom

This technique worked well and was used for the majority of the specimens made in this research; there were however weaknesses to this system. When applying a load to the clamp it would often deform under loading, and after repeated cycles of use, the clamp would experience permanent deformation, requiring straightening.

A second problem observed with this clamping technique is that since approximately 25 percent of the washer was cut out for ease of use, the clamp only applied a load, on the sheet metal, to a certain percent of the perimeter of the sheet metal surrounding the rivet as the rivet was being driven into the sheet metal; allowing minor separation to occur on a small portion of a riveted joint.

When taking cross sections of riveted joints, occasionally the sample would be cut through the area with minor sheet separation, as seen in Figure 2-26 (to the right of the rivet), and sometimes the sample would not be cut through the areas with minor separation, as seen in Figure 2-27; creating inconsistent appearances of joints while samples were made under identical process conditions. (Note that these two specimens were created using different dies).

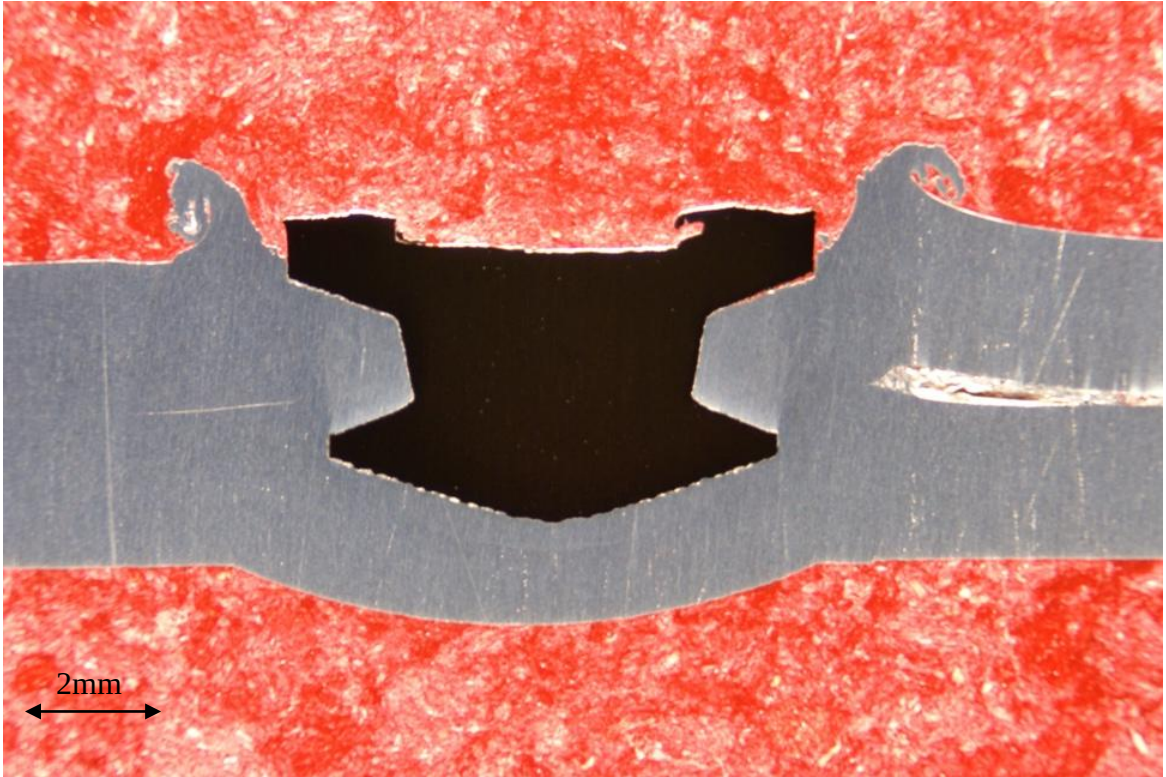


Figure 2-26. Riveted joint, with slight sheet separation to right of rivet

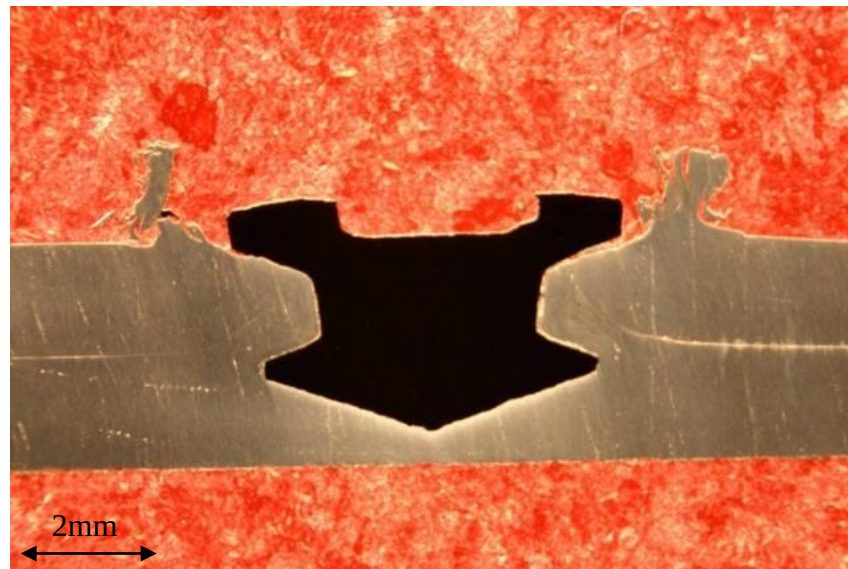


Figure 2-27 Riveted specimen, without sheet separation

To overcome the problems associated with the third generation of clamping technique, a new clamp was devised as seen in figures 2-28 through 2-32. Figure 2-28

shows the clamp with the sheet metal underneath the clamp, not visible. The large hole in the center of the clamp goes approximately 50% through the clamp. At the bottom center of the large hole, there is a small hole that proceeds all the way through the clamp, as seen in Figure 2-29, just large enough for the rivet and driver tip to fit through, for the rivet to reach the sheet metal. Figure 2-30 shows the rivet and driver down, just to the point of making contact with the sheet metal to be riveted. Figure 2-31 is a photo of the bottom view of the clamp; this clamp features a washer welded to the bottom of it, similar to that used in the third generation, while in Figure 2-32 the profile of the clamp is visible. Using this clamp solves the problems associated with the third generation clamping technique, in that a load was applied to the sheet metal in a complete 360 degrees surrounding the rivet, and that it would be impossible to deform this clamp under reasonable conditions. This clamp produced no observed flaws or drawbacks. On a side note it is much larger than is necessary; it was made from a piece of scrap metal found in the UT machine shop, and, in order to save time, was not machined to a smaller size.



Figure 2-28 Fourth generation clamp technique



Figure 2-29 Fourth generation clamp top view

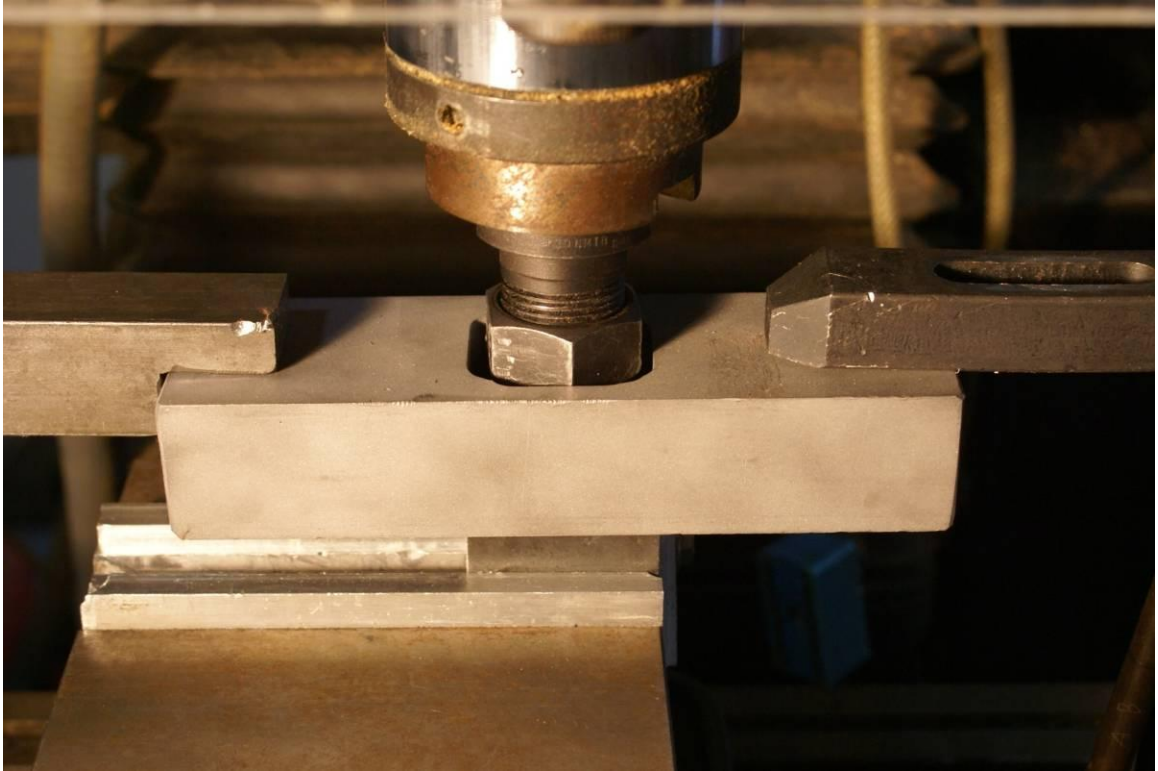


Figure 2-30 Fourth generation clamp in use

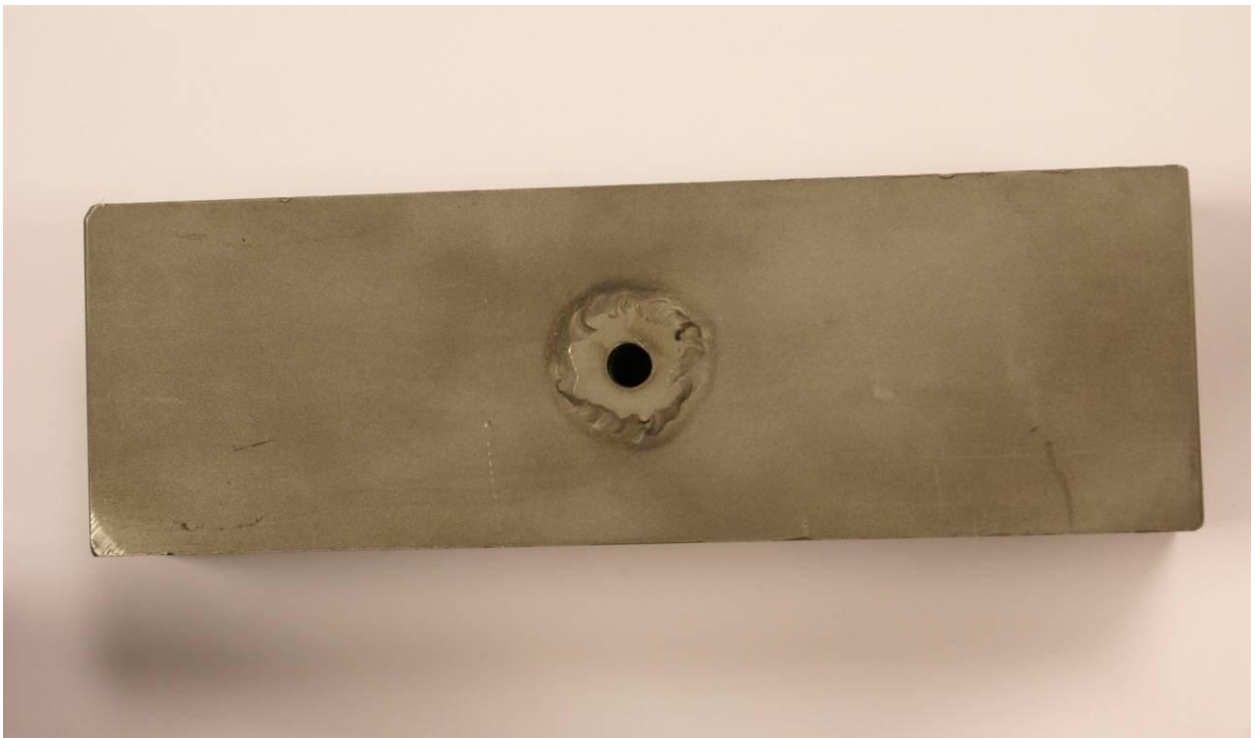


Figure 2-31 Fourth generation clamp bottom view, with welded washer



Figure 2-32 Fourth generation clamp side view

2.3 Driver design

Anxious for progress when the research first started, it was decided that attention should be focused on overall rivet design, consequently little thought was given to the details of how exactly the rivet would be spun and driven into the sheet metal that had no pilot hole. Once rivets were in hand, the first attempt planned to drive them into sheet metal was very simple. The driver used was nothing more than a cylinder, with the flat head of the cylinder mating to the flat head of the rivet. The driver was then spun and applied a downward force to the rivet, counting on nothing more than the frictional force between the rivet and cylindrical driver to transmit the torque and overcome the friction of the rivet against the sheet metal. This attempt did not so much as scratch the sheet metal that it was hoped it would penetrate.

The next attempt involved scoring the head of the cylinder to increase the friction between the rivet and the driver; this ended with identical results to the previous attempt. The next attempt was to use the same cylindrical driver, this time with adhesive backed sandpaper stuck to the cylinder head, again to increase friction between the rivet and

cylinder driver. Again the friction between the rivet and the sheet metal proved greater than the friction between the rivet and sandpaper covered cylinder driver head. Once the rivet stopped rotating with the driver head, the adhesive on the sandpaper failed, and the sandpaper came off the driver tip. Thinking that perhaps if the adhesive had not failed on the sandpaper, this design might have worked, it was decided to simply glue sand directly onto the face of the driver. It was hoped that the sand would provide the grip on the rivet head to keep it spinning during the riveting process, and that the glue would keep the sand securely attached to driver face, unlike the adhesive backed sandpaper. The glue holding the sand to the driver failed, and this attempt was no more successful than all the previous attempts. At this point it was decided to give up on the simple solution that had been attempted.

The machinists at the University of Toledo were witness to the repeated failures; anxious to help, one of the machinists designed and fabricated a driver as seen in Figure 2-33. On the right of figure 2-33 is the driver, and a rivet to match the driver is on the left. This design appeared to be the solution to the driver problem; unfortunately the driver was crushed during the first use under the torsional and compressive loading. Although this driver design did not work, it did act as a guide to point future driver designs in the right direction.

A Phillips style driver as seen in Figure 2-34 seemed a reasonable solution to the driver problem. However, machining a rivet with a Phillips driver slot as seen in Figure 2-35 turned out to be unreasonably complicated and time consuming. A more machineable design was made as seen in Figure 2-36.



Figure 2-33 Driver with matching rivet



Figure 2-34 Phillips driver

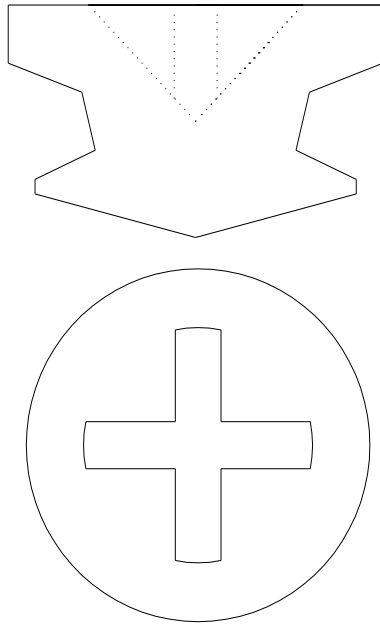


Figure 2-35 Rivet with desired Philips driver slot

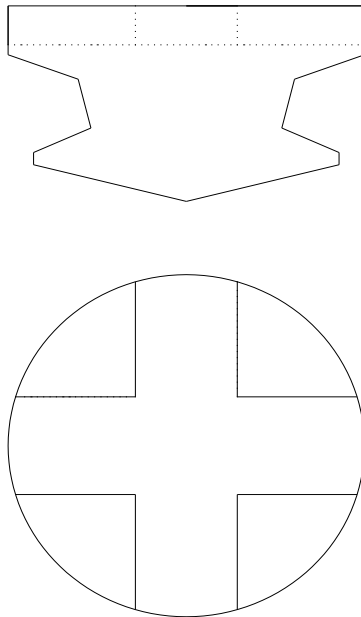


Figure 2-36 Final rivet design with diver slot

A machinist could with ease modify the rivet design in Figure 2-16 to a usable rivet as seen in Figure 2-36. A Phillips screw driver was then purchased, handle cut off, and the very tip of driver cut off, to provide a flat surface to mate with the slots on the rivet;

the inside corners of driver filed down, to ensure the driver would fit inside of the rivet driver slots. The first Phillips driver purchased was a number 3 driver, and little thought was given to this choice. After the driver had been assembled as previously mentioned, the first successful joints were formed. However, the success rate was not 100 percent: occasionally the rivet would start to wobble as it was spinning, and then be shot out from under the driver; other times the rivet would again stop spinning as was the problem before the new driver was used. The driver would continue to spin with a heavy compressive load applied to the rivet, stripping the rivet head, and damaging the driver. Damage to the driver was sometimes fixable with a file, and other times needed to be replaced. After going through a few screw drivers in this manner it was concluded that a reasonable driver had not yet been found. Shopping for another screwdriver after yet another driver had been damaged beyond the point of repair; it was decided to buy a number four Phillips screw driver instead of the number threes that had been purchased up until that point. The diameter of the number 4 is larger than the number 3; this increase in diameter of the number 4 Phillips driver prevented the occasional problems experienced with the number 3 Phillips driver. This was accomplished by the fact that the number four driver was approximately the same diameter as the rivet, while the number three driver was of a smaller diameter than the rivet. When the driver had a smaller diameter than the rivet, the driver focused the downward loading towards the center of the rivet, as opposed to applying the load evenly throughout the head of the rivet all the way towards the perimeter. This centralized loading on the rivet provided less control of the rivet, and was responsible for the occasion problem of rivet wobble and ejection. The centralized loading was also responsible for the other problems with this design: as the

rivet is being spun and driven into the sheet metal a large amount of torque is required to overcome the frictional force of the rivet against the sheet metal, occasionally this friction was too high for the rivet. When the friction became high enough, the rivet would stop spinning while the driver continued spinning; this would instantly strip out the driver slots on the rivet head (destroying the rivet) and damaging the driver. When using the new driver constructed from a number four Phillips, this was no longer an issue, the larger diameter of the driver distributed the torsional stress evenly all the way to the perimeter of the rivet during insertion, providing the strength to overcome the frictional forces. This driver provided the reliability that was required for this research.

3 Friction-stir Riveting Process

A CNC milling machine was used for the riveting process. The die would be clamped in the table clamp, and the two layers of sheet metal to be riveted together would be placed on to the top of the die. The clamp to be used (as described in Section 2-2) would be placed on the sheet metal in alignment with the driver, so that the clamp would not interfere with the driver as it spun and drove the rivet into the sheet metal, and clamped down with adequate tightness to prevent the sheet metal separation seen in Section 2-2. A rivet would be placed on the tip of the driver and held in place with a magnet. The table of the mill would be raised manually until the rivet came into contact with the sheet metal; in an ideal situation if the rivets were all exactly the same length, the table would be raised to a set height, as opposed to raising the table until the rivet came into contact with the sheet metal. Once the sheet metal was raised to come into contact with the rivet, the magnet used to temporarily hold the rivet to the driver would be removed. The CNC milling machine was preprogrammed to spin a rivet at a predetermined spindle speed, drive the rivet into the sheet metal at a specified feed rate, to a certain depth. The spindle speed used for this research varied from 1000 to 3000 R.P.M.'s, and the typical feed rates that were used ranged between 0.05 and 0.20 inch per minute. Once the program was started on the mill, the feeding was usually paused to allow the spindle to spin the rivet, with a slight downward load applied to the sheet metal,

for 60 seconds, to generate heat from friction to preheat the sample before the rivet was driven into the sheet metal; although the necessity of this 60 second preheat is questionable, more samples would need to be taken to prove if preheating has any effect. After the 60-second warm up, the CNC mill would drive the spinning rivet into the sheet metal as specified. At the end of the cycle the clamp was manually removed from the top of the sheet metal, and the joint was then ready for analysis.

3.1 Material flow, and interface geometry at different depths of penetration

Figures 3-1a-f show a cross sectional view of progressive steps of a rivet penetrating sheets of aluminum at increasing depths. It should be noted that the geometry of the rivet in Figure 3.1a appears unique compared to the rest of the rivets in Figure 3-1. The rivet in Figure 3-1a has a flat horizontal top, which is different from the others in Figure 3-1. Actually all the rivets in Figure 3-1 are identical; the difference in appearance is the result of the different rotational angles of the rivet with respect to the section line using an abrasive disc cutter to cut the specimen in half, in order to view the cross section. Figure 3-2 depicts the possibilities of cutting two identical rivets in half by an abrasive disc cutter (the thick black line represents the disc cutter). When cutting a specimen as in Figure 3-2a a cross section similar to that in Figure 3-1a would be produced, and when cutting a sample across the slots on the rivet head as in Figure 3-2b the resulting cross section of the rivet would resemble those in Figures 3-1b-f. One should be aware that care must be taken when cutting small samples like these for metallographic examination. One must not cut the sample directly along the center, but leave an approximately 1-2 mm offset, as seen in Figure 3-2. One must take into account the material lost during the disc cutting, approximately 1mm, and the material lost during

grinding and polishing phase, again around 1mm, or else the finished cross section sample will not be at the center of the rivet, but off to one side as shown in Figure 3-3. All photos in Figure 3-1 were taken with an identical die, identical rivet penetrating the identical two sheets of 2 mm thick aluminum alloy. Figures 3-1a and b are slightly different from other photos in that they have a layer of cement above the top layer of aluminum. The cement was used merely to hold the rivet in place during cutting, grinding, and polishing as in these two cases the rivet/sheets were not bonded together. The cement is unnecessary for other specimens due to sufficient rivet penetration.

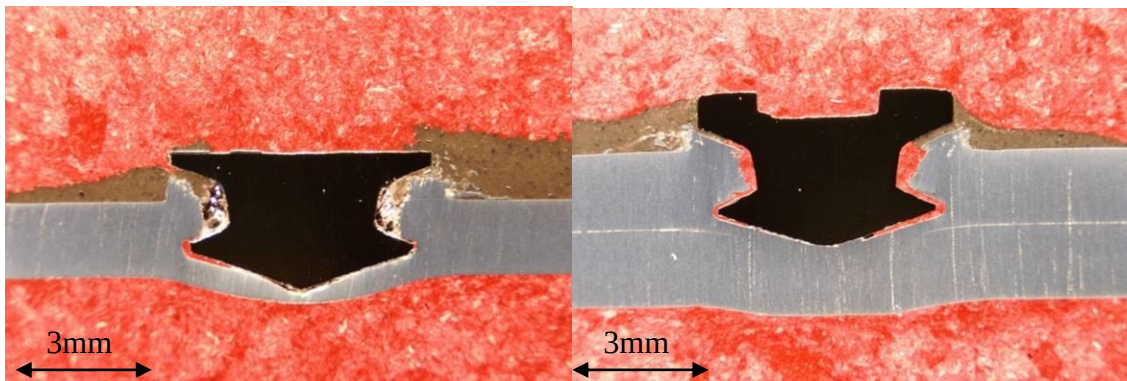


Fig 3-1a Inserted 2.5 mm

Fig 3-1b Inserted 2.7 mm

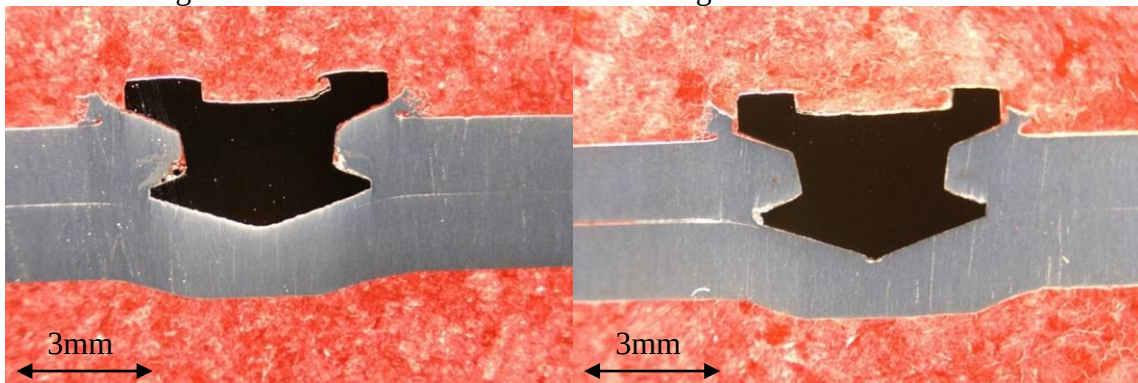


Fig 3-1c Inserted 2.8 mm

Fig 3-1d Inserted 3.0 mm

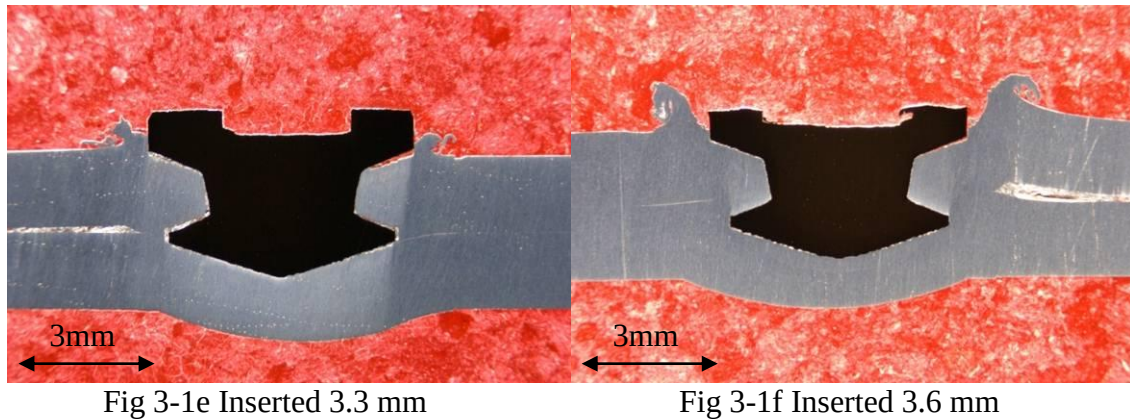


Figure 3-1a shows a rivet penetrating to a depth of 2.5 mm. Only one layer of aluminum is present in this photo because the lower layer of aluminum did not bond with the upper layer. The aluminum is allowed to deform under the loading applied from the rivet to take the shape of the die; this is the reason why a rivet penetrating 2.5 mm did not pierce a sheet of aluminum 2 mm thick.

An interesting observation from this photo is that the softened aluminum starts to flow back towards the rivet stem after the rivet bottom flange passes through the material. Figure 3-1b depicts a rivet penetrating to a depth of 2.7 mm. In this sample the upper layer of aluminum does bond with the lower layer, but if one looks closely at this sample one can see the horizontal interface between the upper sheet and the lower sheet; as the interface approaches the rivet from the left and the right, the interface curls downward managing to stay below the rivet. The rivet does not fully pierce the upper layer of aluminum, but it does form a weak bond between the two sheets of aluminum merely from the heat generated and the compressive loading applied during the riveting process. The softened aluminum flowed back towards the rivet stem a little more successfully than in Figure 3-1a, it appears that the stirred aluminum started to make contact with the back surface of the rivet head, which should help to direct the aluminum back towards the rivet

stem. Continued riveting made the lower surface of the lower sheet of aluminum under loading to take the shape of the die. It did not, however, fully take the shape of the die at this stage of riveting. The sample in Figure 3-1c was taken at a depth of 2.8 mm. The softened aluminum almost completely filled the void surrounding the rivet stem; a close comparison with the previous sample in Figure 3-1b shows little change in geometry. The bottom surface of the lower layer of aluminum at this stage does deform to the shape of the die more noticeably than that in Figure 3-1b.

When the penetration was increased to a depth of 3.0 mm as in Figure 3-1d, the softened aluminum filled the entire void surrounding the rivet stem. The interface between the two sheets of aluminum again curled down to stay below the rivet at this time, but with a closer inspection towards the bottom tip of the rivet it can be found that the rivet did fully pierce the upper layer of aluminum. In this specimen the void next to the rivet trunk was fully filled and the die cavity was filled more than in the previous stage, but still not completely. When penetrating to a depth of 3.3 mm as in Figure 3-1e, the void surrounding the rivet stem was kept completely filled, and the die appeared completely filled. The rivet appeared to completely puncture the top sheet of aluminum throughout the entire width of the rivet bottom flange. The sheet interface still curled downward. Figure 3-1f shows a rivet penetrating to a depth of 3.6 mm. At this stage the void surrounding the rivet stem was again entirely filled, the die was completely filled, and the rivet completely punctured the top sheet of aluminum and penetrated into the bottom sheet. Upon close examination of the interface geometry, it can be seen that the interface is now approximately horizontal, with a slight upward curve, which is preferable, instead of curling down.

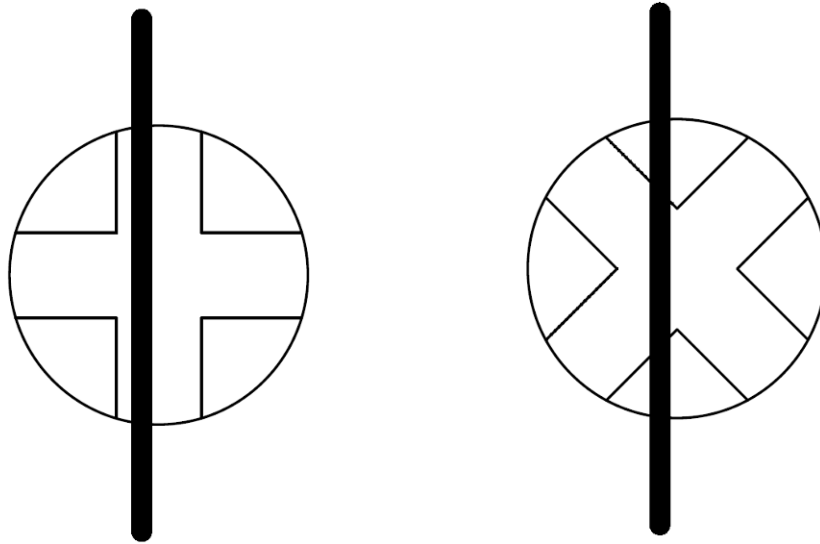


Figure 3-2 Orientation of bisecting a riveted joint

Figure 3-3 shows the results of cutting a riveted specimen in half along the center line without offset as shown in Figure 3-2; and then grinding the sample too aggressively.

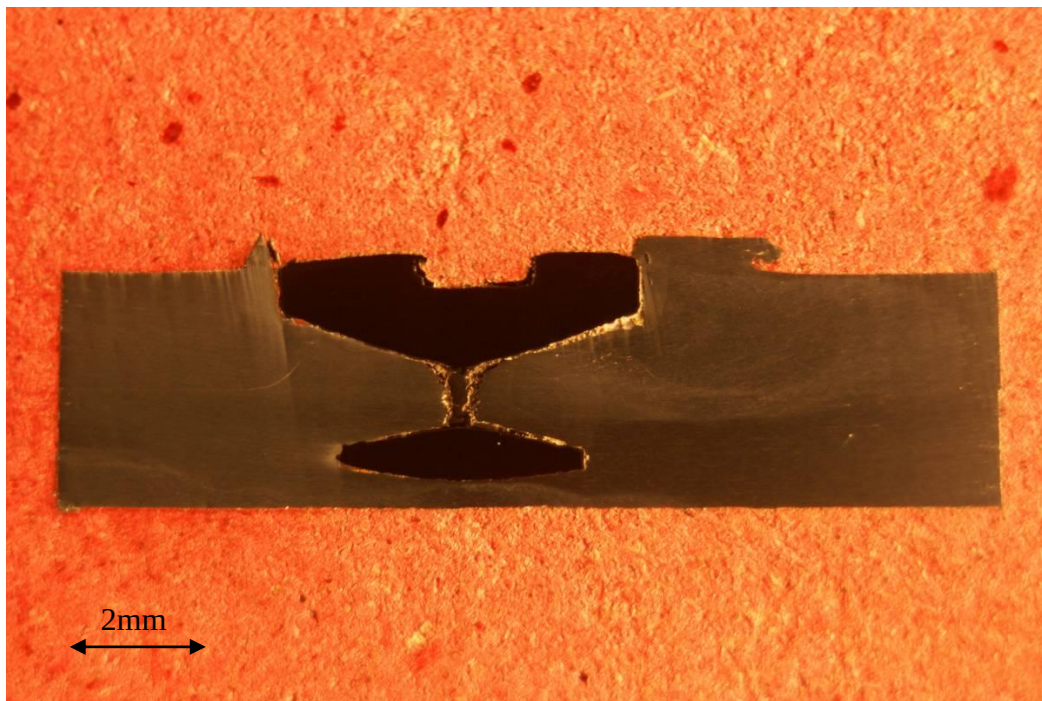


Figure 3-3. Cross sectional view of riveted joint cut without offset sectioning

4 Friction-Stir Riveting Process

Characterization

4.1 Effect of die on interface geometry

The use of a die underneath the sheet metal during the riveting process proved essential for maintaining reasonable joint interface geometry, and hence a quality joint. The goal of using a die being to insert the rivet to the proper depth, while maintaining the ability to control the shape and orientation of the interface. Figure 4-1 shows a good friction stir riveted joint; the rivet is inserted into the sheet metal to the proper depth, the interface, visible on the left, is mostly horizontal and points towards the vertical center of the rivet, neither curling up towards the rivet head or curling down towards the rivet bottom flange. The die used to make the joint in Figure 4-1 is responsible for the concave up shape of the sheet metal, visible towards the bottom center of the specimen. The extra material that fills the die also serves as a barrier to guard against corrosion, and provide a joint with an air tight seal.

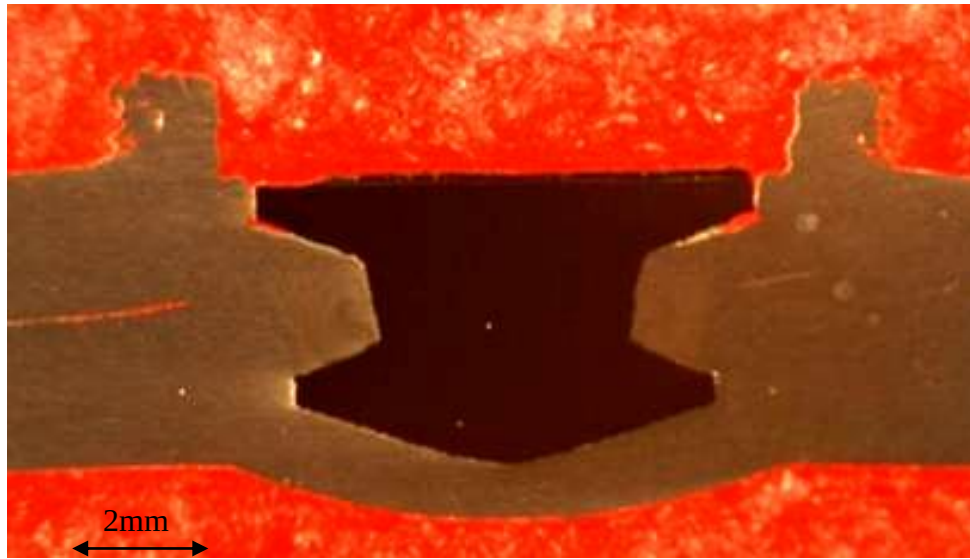


Figure 4-1 Typical friction stir riveted joint

Figures 4-2a and b are cross sectional views of a joint with a rivet penetrating to a depth of 3.8 mm without the use of a die during the riveting process. Figure 4-2a was taken with a standard camera and lens using an extension tube to bring a subject closer to the camera than is normally possible, and hence photographing the subject in higher detail (the majority of the macro photos in this work were taken in such a manner). The photograph in Figure 4-2b (of the same specimen) was taken after etching, and this time through a microscope, with an 80X magnification, instead of a standard camera lens. Photographing through a microscope offers a few advantages and one disadvantage. The main advantage is having greater magnification capability than using a standard lens with an extension tube. Secondly using a microscope to take photos can be more forgiving when focusing, versus a standard lens with an extension tube (which has a very shallow depth of field). Lastly the light source from a microscope passes through the lens striking the sample perpendicularly and reflecting straight back into the lens and out the eyepiece; the light striking the sample nearly perpendicularly provides greater detail and a new perspective when compared to light reflecting off the sample at a steep angle as is

required when photographing a sample using an extension tube due to the closeness of the sample to the lens, often times only 1-2 cm.

The disadvantage of using a microscope is the stricter limitation to wide angle viewing than that provided by a conventional camera lens (one cannot see the entire specimen at once). To overcome this problem Figure 4-2 b is actually a collage of 6 photos stitched together; this stitching technique is responsible for the inconsistency in exposure seen in Figures 4-2b, 4-3b and 4-4b. From Figures 4-2a and b the lack of die is evident when viewing the bottom surface of the lower sheet of aluminum which is completely horizontal and lacks a downward bulge seen in Figures 4-3 and 4-4. All of the material displaced by the rivet during penetration is forced up and most is ejected as metal 'chips' during the riveting process; this is partially evident when looking to the left and right of the rivet head in Figure 4-2a. In Figure 4-2b the geometry of the interface becomes apparent, and the interface can be seen to curl upwards steeply towards the rivet head. This is not desirable, as the interface comes close to contacting the rivet head. Figure 4-3a and b are a specimen with a penetration depth of 3.8 mm but this time using a small die with a volume 7.33 mm^3 ; photographed with different techniques. The effect of die can be seen in the downward bulge of the bottom of the lower sheet. Figures 4-4a and b are on a sample with the same penetration depth of 3.8 mm, but using a larger die with a volume of 21.2 mm^3 . Again the effect of the die is apparent by the downward bulge on the bottom of the lower sheet of aluminum underneath the rivet. Close attention should be given to the interface geometry in Figures 4-2b, 4-3b and 4-4b; as all samples were prepared under identical conditions to identical depths; and the only difference is the use of a die underneath the sample during riveting. In Figure 4-2b (without a die) the

interface curls upward too steeply as previously discussed; in Figure 4-3b (with a small die) again the interface curls upward, but of a lesser degree. In Figure 4-4b the interface is nearly horizontal, or perhaps curling slightly downwards. It should be mentioned that the sample in Figure 4-4 is not an ideal joint due to the inadequate rivet penetration depth, as this specimen was taken merely as a comparison to the ones shown in Figures 4-2 and 4-3, not to represent a quality riveted joint.

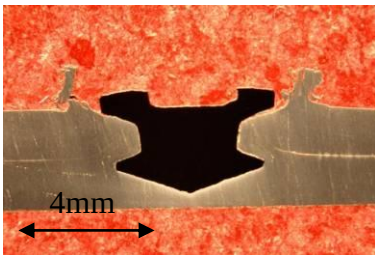


Figure 4-2a. No die, unetched

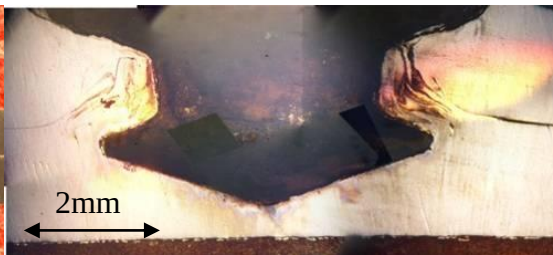


Figure 4-2b. No die, etched

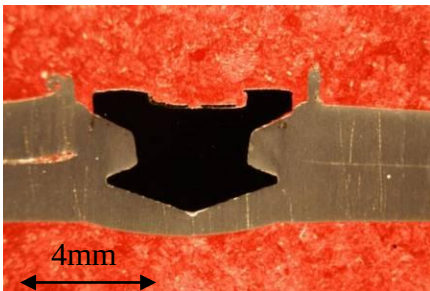


Figure 4-3a. Small die, unetched

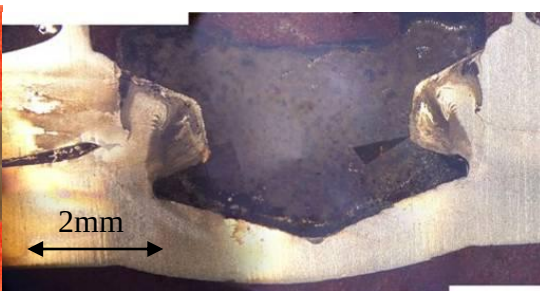


Figure 4-3b. Small die, etched

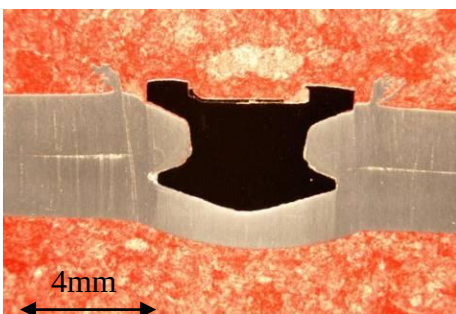


Figure 4-4a. Large die, unetched

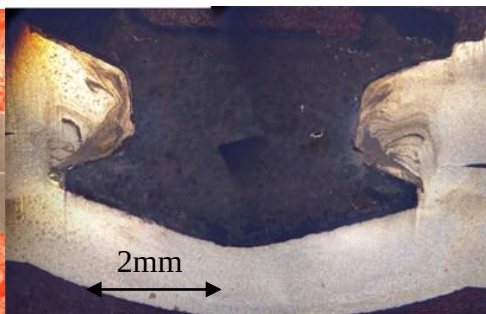


Figure 4-4b. Large die, etched

Figure 4-5 is the drawings of two different dies used for the vast majority of the samples taken during this research, both dies have spherical cavity caps. The ‘large’ die has a cavity volume of 21.2 mm^3 , and that for the ‘small’ die is 7.33 mm^3 .

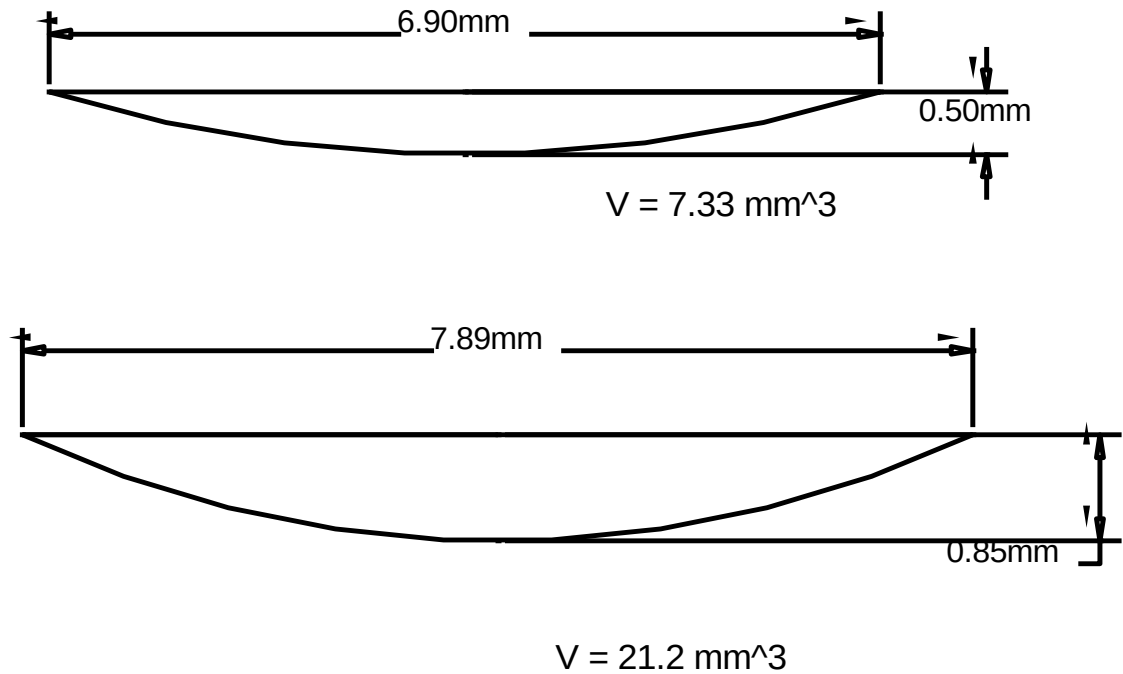


Figure 4-5 Small and large dies

Figure 4-6 depicts the riveting procedural setup with the die (labeled in figure) placed underneath the sheets of aluminum. Not visible in this photo, but located directly underneath the rivet on the die is the hemispherical cap hollow that forms the downward bulge seen in figures 4-4a and b.



Figure 4-6. Riveting procedure setup with a die

Finite element analysis reveals that a joint with a horizontal interface is the most desirable in terms of joint strength, that is with the interface neither curling up, nor down. In reality producing a completely horizontal interface proved to be nearly impossible. The volume of the die should be equal to the volume of the rivet penetrating below the original interface of the sheet metal, and then the rivet should penetrate to the material to the exact depth, to displace the desired volume, to produce the desired horizontal interface. This proved to be difficult, while using a CNC mill to drive the rivet to the exact depth was not a problem, minor inconsistencies of just a few thousands of an inch in the length of the rivet made rivet insertion to the exact depth difficult. It should also be noted that while the F.E.A results suggest that a completely horizontal interface is the

best, experimental results reveal that a rivet penetrating slightly too deep, producing an upward curving interface, is very little different from that of a completely horizontal interface.

4.2 Metallographic Analysis of the riveted joint microstructure

In order to gain further insight into the microstructure of the base material and any potential metallurgical changes brought on from the riveting process, specimens were etched to aid in microscopic analysis.

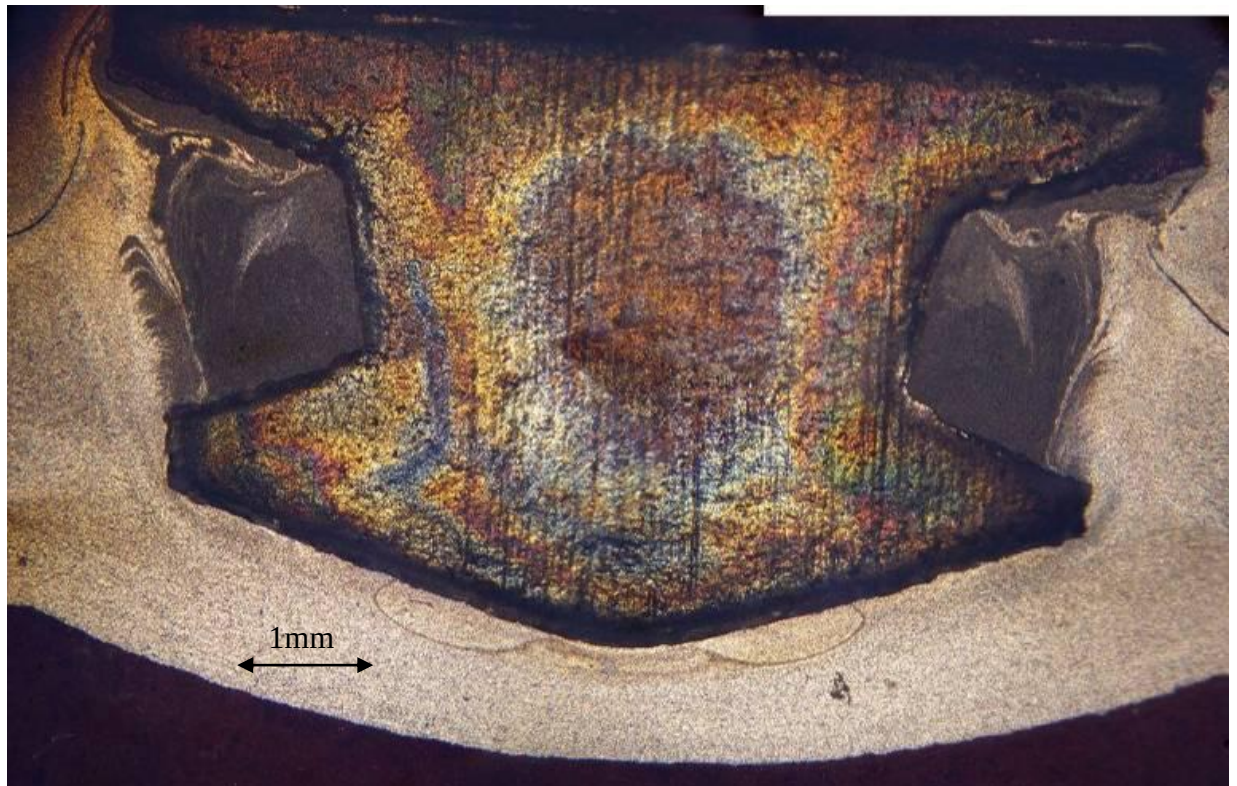


Figure 4-7 Over etched specimen of an Al joint

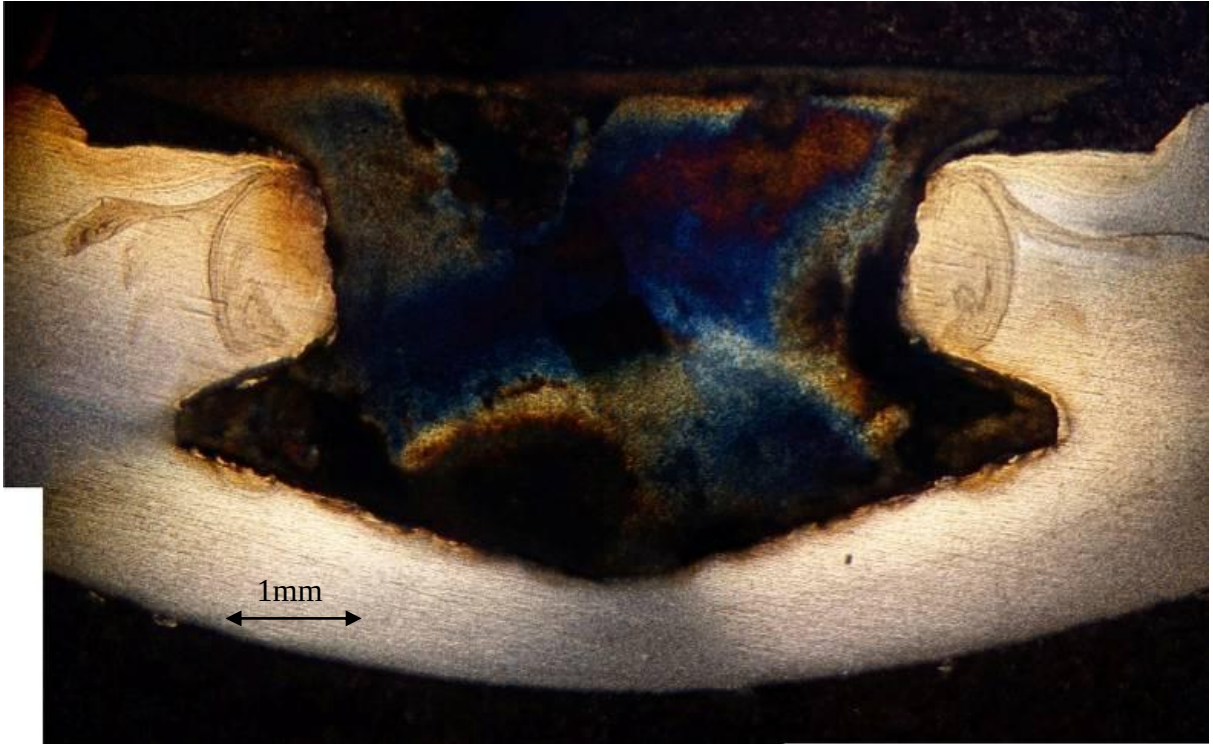


Figure 4-8. Under etched sample

Various etching procedures were tested to reveal the microstructures of the friction-stir riveted joints. After many trials an optimal procedure was developed. The etching involves submerging the sample in an acid bath that is 25 percent nitric acid and 75 percent phosphoric acid, and the mixture is heated to 60 degrees C. The duration of time for the submerging in the acid bath is a function of the concentration of acids, for this research 30 seconds of etching was found proper. Figure 4-7 (the same sample as in Figure 4-2, etched for 2 minutes as in Figure 4-2d) shows a sample that was likely over etched; while Figure 4-8 is of a sample etched for 15 seconds that would have benefited from a longer etching. Figure 4-9 shows 4 different views of the same sample taken with progressively longer etching viewed through a microscope with an 80X magnification. In these photos the rivet is on the side of the image, with the rivet head in the upper right,

the rivet trunk in the central right, and the rivet bottom flange in the lower right corner of the images. On the left side a line is visible, entering from out of the frame, which is the interface between the upper and lower layers of aluminum. The samples in Figure 4-9 reveal the effect of progressively etching time on the aluminum and steel of the samples. The steel of the rivet in Figure 4-9a starts off polished similar to a mirror, then oxidizes almost instantly when etched, after 2 minutes in the acid bath the steel rivet is covered with a thick layer of multi-colored rust. The goal of the etching is to observe the aluminum though and not the steel rivet so little attention was paid to the steel. Etching for around 30 seconds appeared to work best for the samples taken during this research.

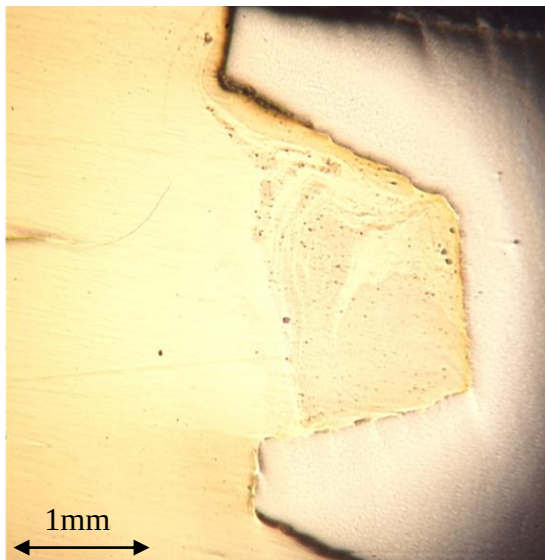


Figure 4-9a. Unetched

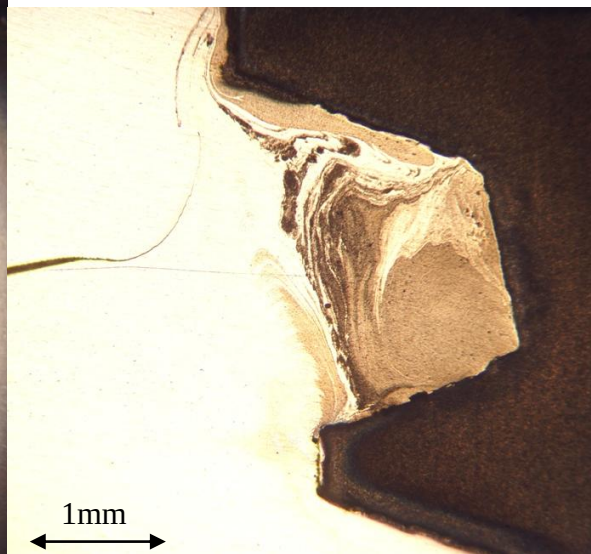


Figure 4-9b. Etched 30 seconds

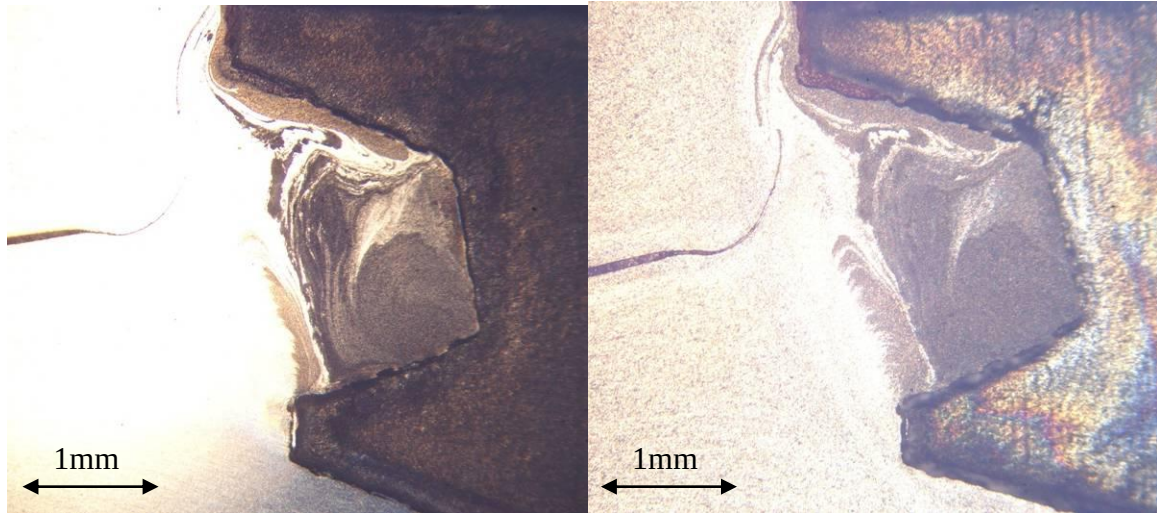


Figure 4-9c. Etched 1minute

Figure 4-9d. Etched 2 minutes

4.3 Joining of various materials

All previous samples seen in this thesis join two sheets of 2-mm aluminum alloy 5754 as seen in Figures 4-10 and 4-11. Figure 4-11 is a microscopic view of the same sample as seen in Figure 4-10. In addition to the joints made on aluminum alloy 5754, magnesium alloy AZ31 was also used in this research for the feasibility of friction-stir riveting of Mg alloys and dissimilar metals.



Figure 4-10. Typical riveted aluminum joint

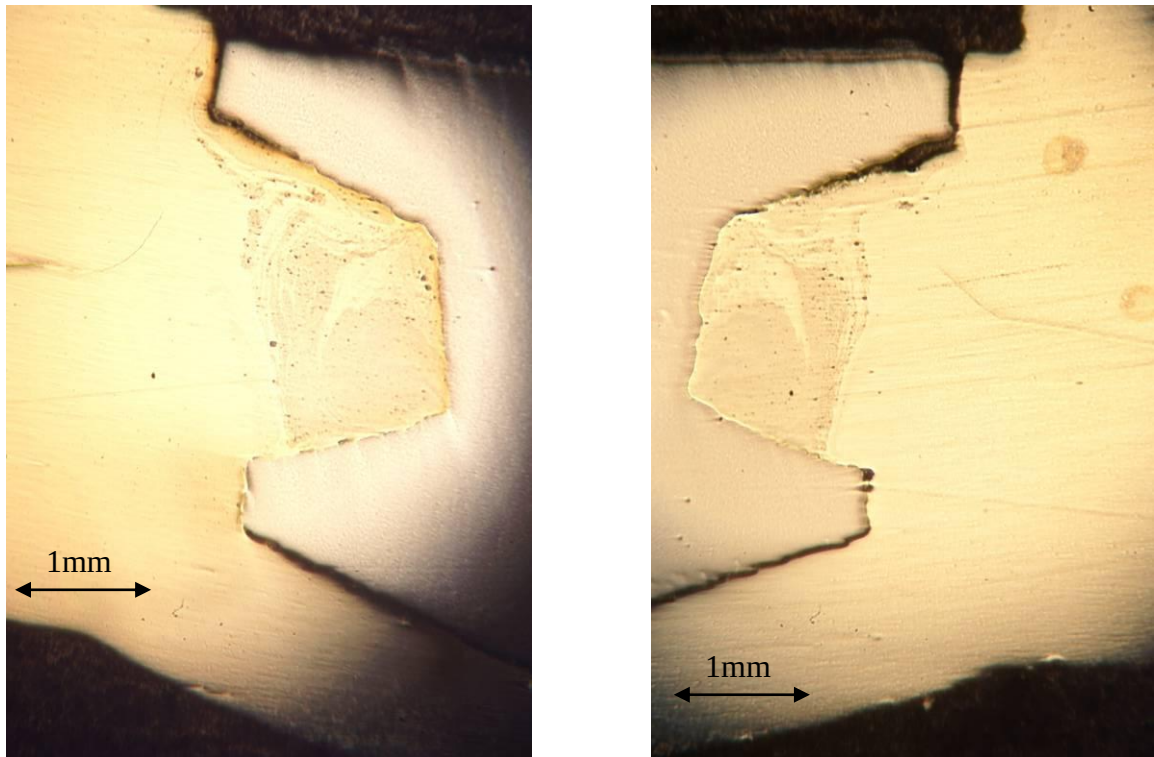


Figure 4-11. Microscopic view of aluminum joint

Figures 4-12 and 4-13 are of a sample riveting two sheets of 2-mm sheets of magnesium alloy AZ31. The magnesium can be seen to be discolored above the rivet bottom flange and surrounding the rivet stem. This discoloration appeared to form during the grinding and especially the polishing phase of sample preparation, possibly a reaction with the polishing compounds used. When the sample was originally cut with a disc grinder it was not discolored, and as soon as the polishing of the sample was complete and the sample was washed and dried the evolution of the discoloration would stop. These samples were taken in the exactly same manner as the aluminum samples and they were also prepared in the same manner.

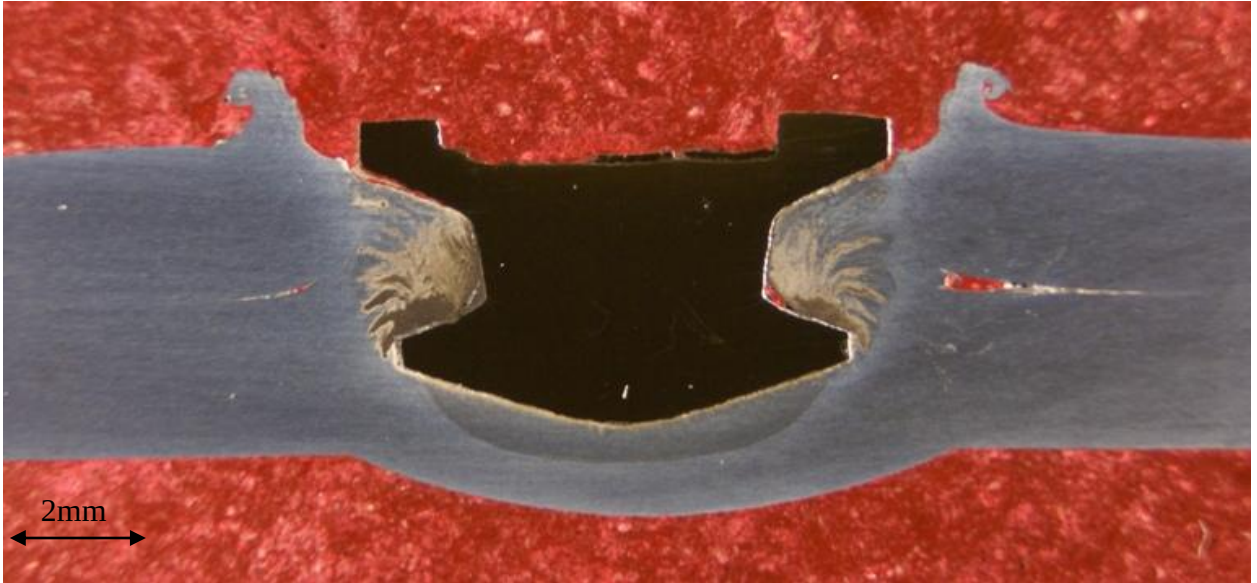


Figure 4-12. Two sheets of magnesium alloy riveted together



Figure 4-13. Microscopic view of magnesium sample

In Figures 4-14 and 4-15 the cross section of the same composite joint between Al and Mg is shown. Figure 4-14 is a photo taken with a standard camera, lens while using an extension tube; Figure 4-15 has two photos taken through a microscope, highlighting

the area of interest. In this sample magnesium alloy AZ31 was used as the top layer, while aluminum alloy 5754 was used on the bottom.

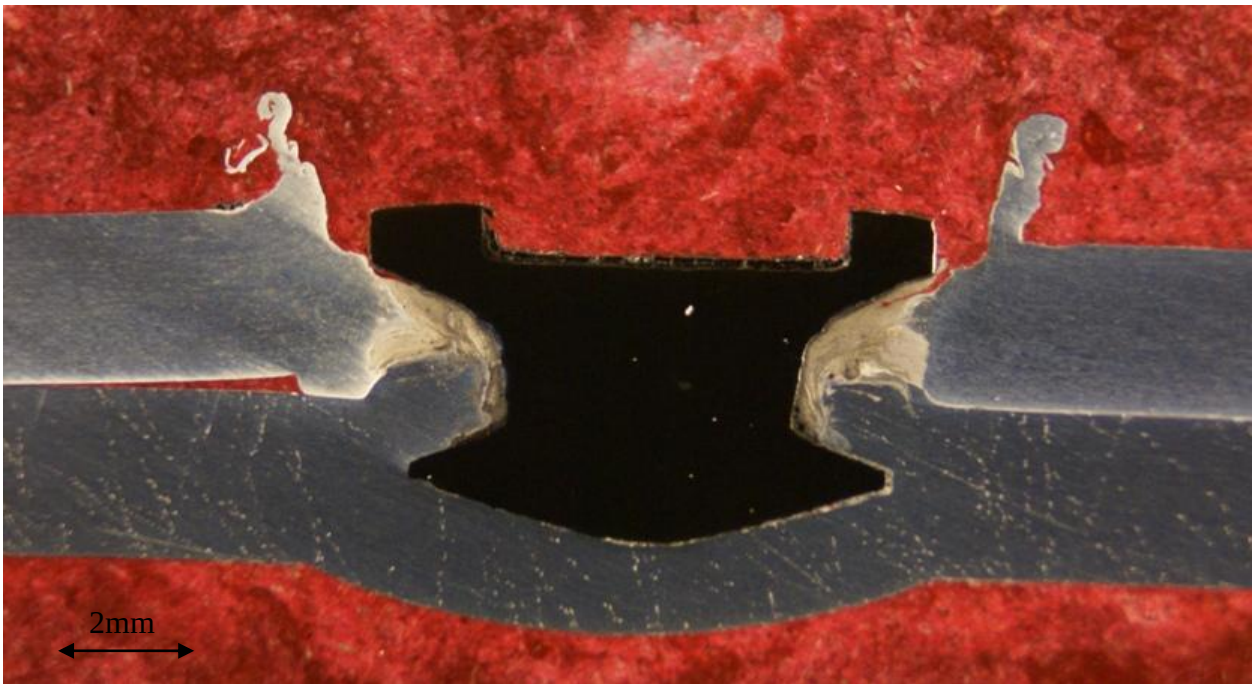


Figure 4-14. Composit joint macro view

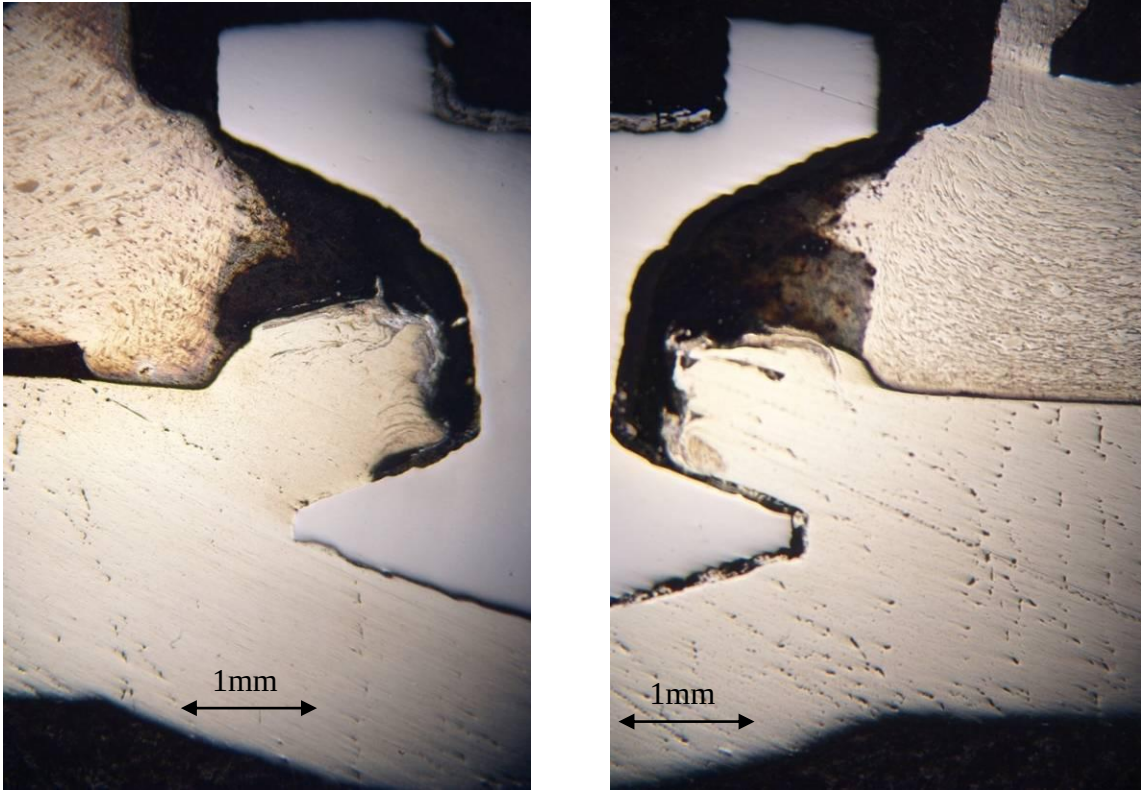


Figure 4-15. Composite joint micro view

The joint featured in Figures 4-16 and 4-17 is also a composite joint, with a layer of aluminum alloy 5754 on top riveted to a layer of magnesium alloy AZ31 on the bottom. There are three layers of separate materials present in this sample, all clearly distinguishable from each other. The steel rivet appears black in Figure 4.16, the upper layer of aluminum appears dark bluish grey, and the lower layer of magnesium as a lighter gray. An interesting observation is that a ‘cap’ of aluminum stuck to the bottom rivet flange during insertion is unlike what was seen in Figures 4-16 and 4-17 when the magnesium was on top and the aluminum on the bottom. It should also be noted that there does not appear to be any meaningful mixing of the two separate sheets being riveted together in this sample or the previous sample in Figures 4-16 and 4-17, as was

seen earlier when two sheets of aluminum or two sheets of magnesium were riveted together, as seen in Figures 4-3 and 4-4.

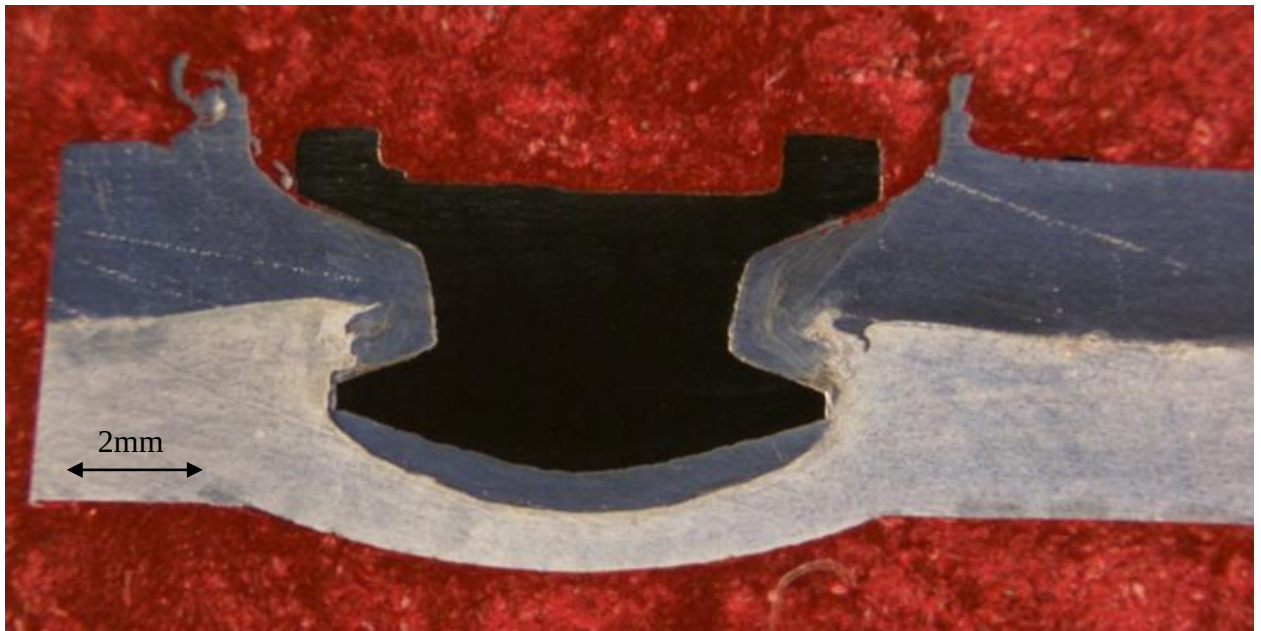


Figure 4-16. Composite joint, macro view



Figure 4-17. Composite joint, microscopic view

4.4 Element mapping with electron scanning microscope

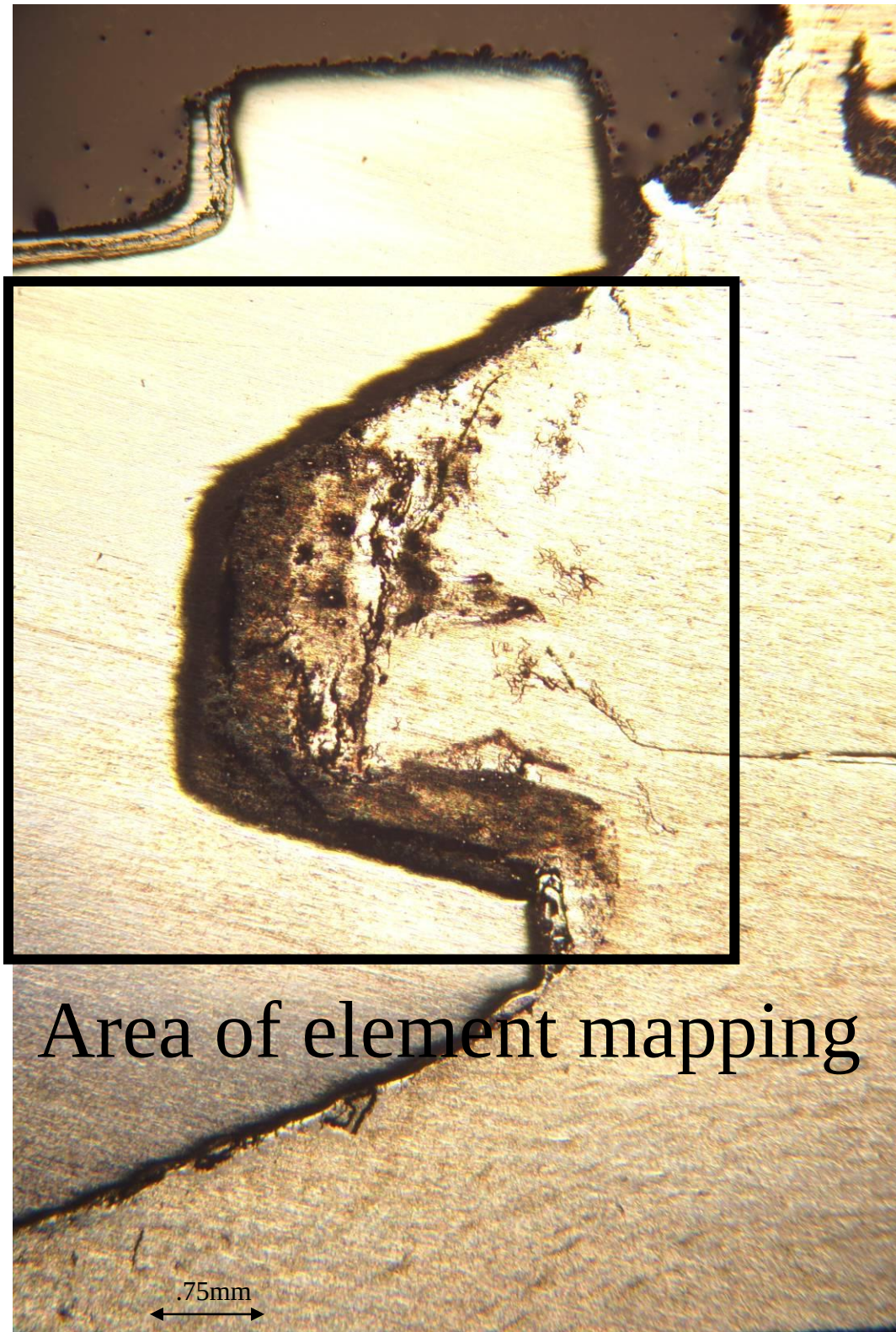


Figure 4-18. Section of rivet to undergo element mapping

The boxed-in area in Figure 4-18 shows the section of a sample to undergo element mapping using an electron scanning microscope. This sample was made using two sheets of magnesium alloy AZ31. Figure 4-19 displays the image from the scanning electron microscope, with the rivet taking up the left half the photograph.

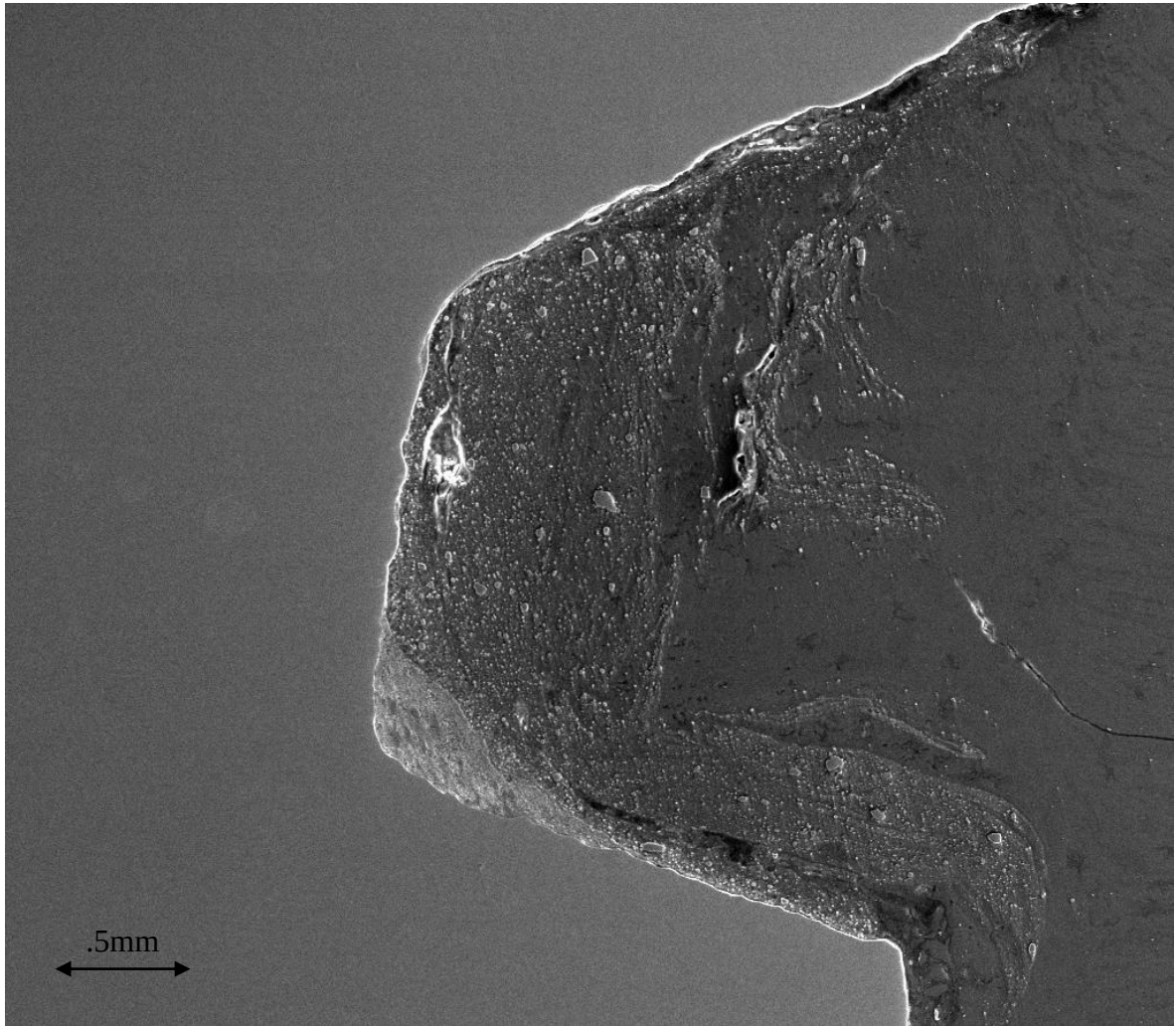


Figure 4-19. Image from scanning electron microscope

As can be seen in Figures 4-20 through 4-25 the composition of the O1 tool steel is mainly iron (Figure 4-20), with traces of carbon (Figure 4-21), manganese (Figure 4-22), chromium (Figure 4-23), nickel (Figure 4-24), and silicon (Figure 4-25). While the

composition of AZ31 magnesium alloy is mainly magnesium (Figure 4-26), with traces of zinc (4-27), manganese, silicon, and aluminum (Figure 4-29). The polishing compound used to prepare this sample aluminum oxide, efforts were made to thoroughly wash samples after polishing, but figures 4-28 and 4-29 suggest that more of an effort to clean this sample after polishing would have been worthwhile.

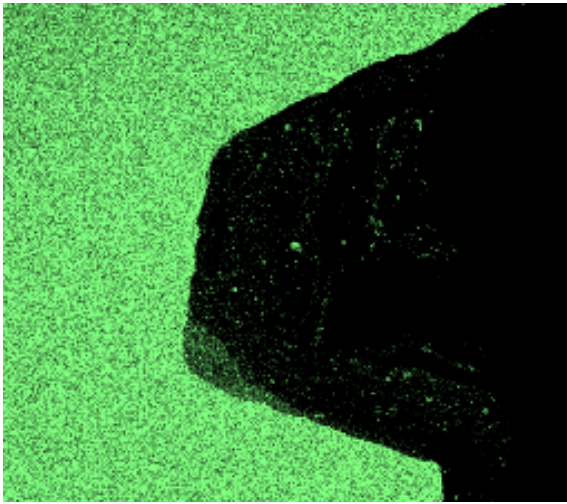


Figure 4-20. Iron

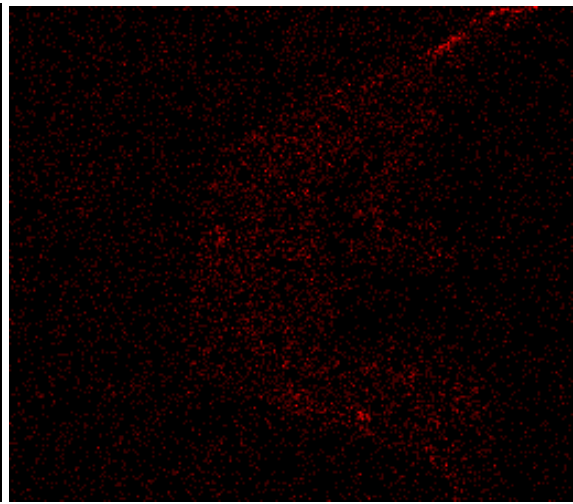


Figure 4-21. Carbon

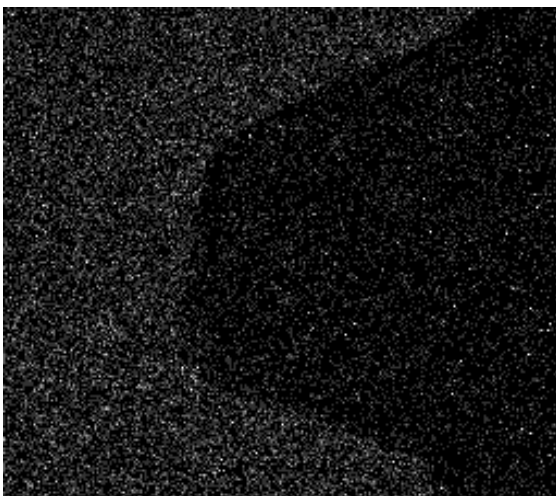


Figure 4-22 Manganese

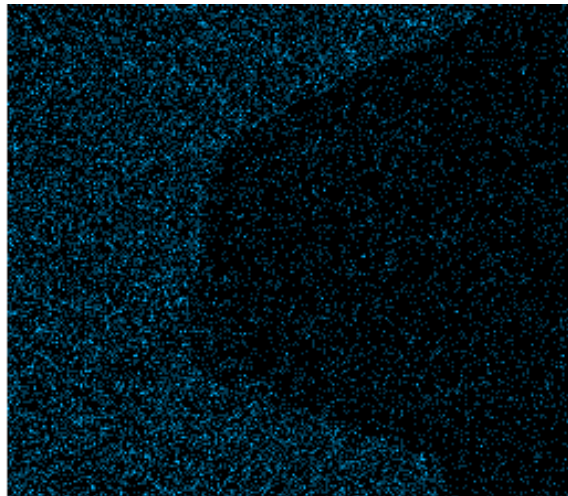


Figure 4-23. Chromium

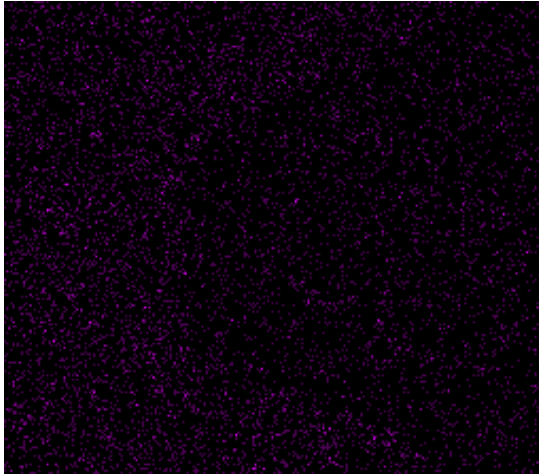


Figure 4-24. Nickel

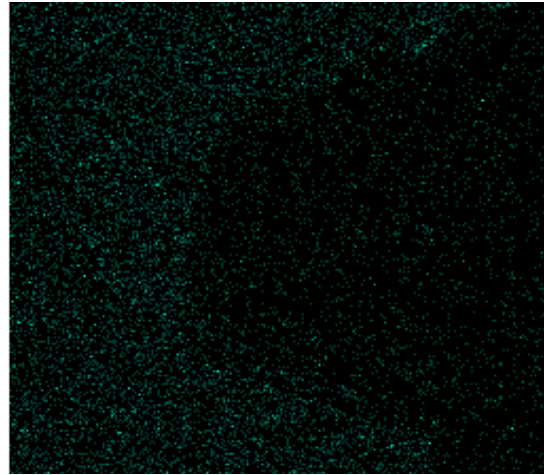


Figure 4-25. Silicon

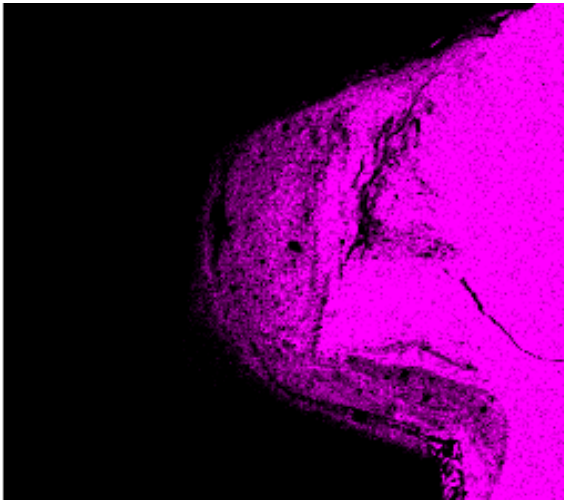


Figure 4-26. Magnesium

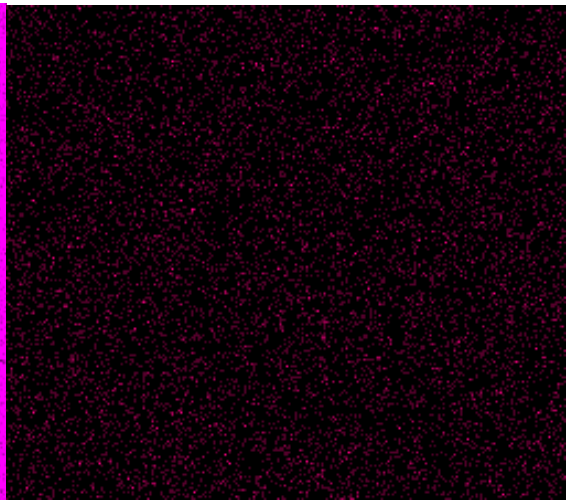


Figure 4-27. Zinc

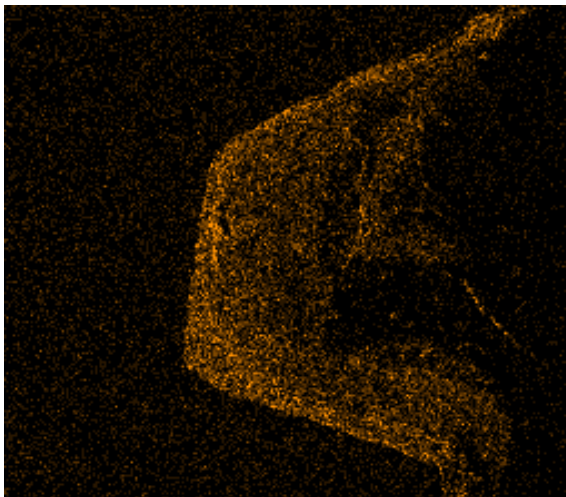


Figure 4-28. Oxygen

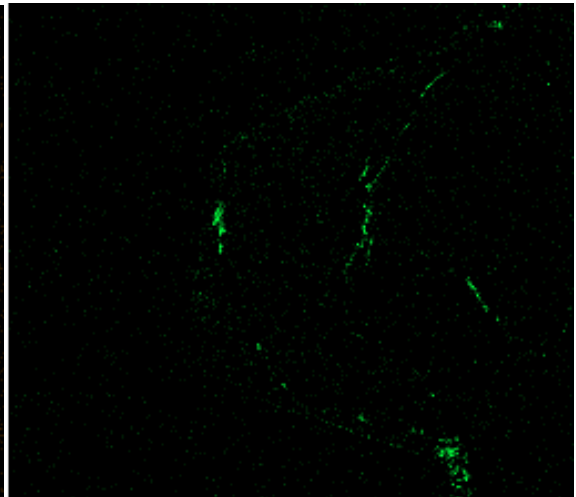


Figure 4-29. Aluminum

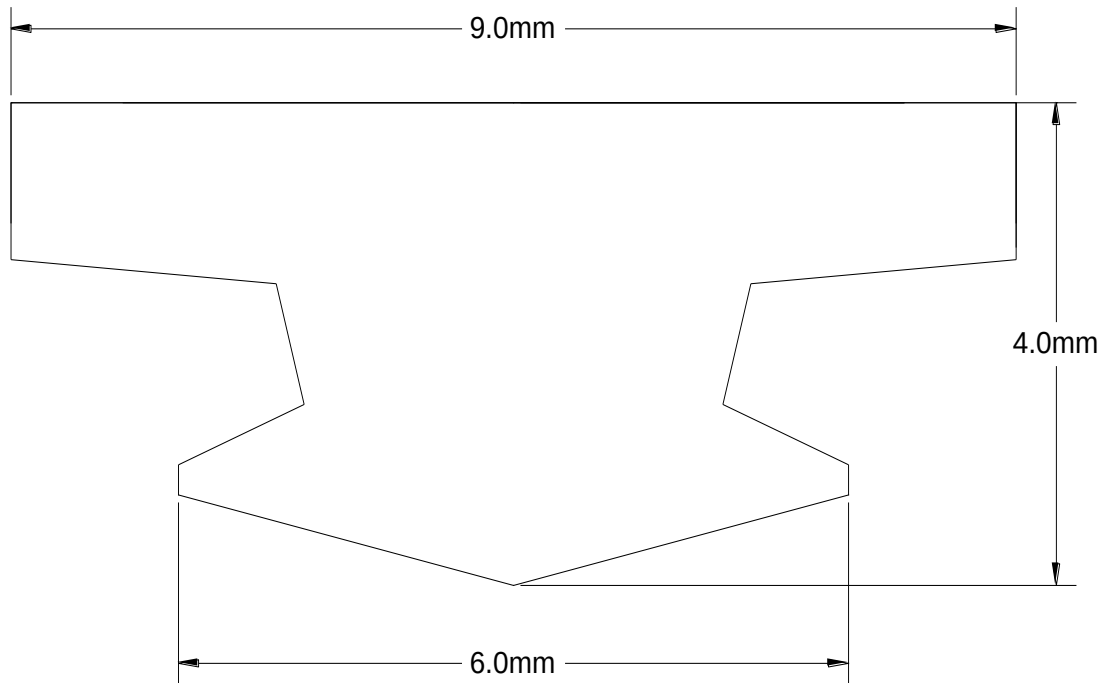
5 Conclusion

5.1 Summary

Friction-Stir riveting forms a joint that is comparable in strength to resistance spot welding, or self-piercing rivets. This technique can be applied to joining sheets of magnesium alloy AZ31 together without the drawbacks associated with resistance spot welding or self-pierce riveting. The strength of a friction-stir riveted joint is heavily dependent upon the depth of insertion of the rivet, and is also to a lesser extent dependent upon the rotational speed during insertion and the rate of insertion. Further research is required to prove the importance of these factors in joint strength.

5.2 Future work

Rivet design evolved drastically over the course of this research, and the results of the final design were suitable. Further studies in this area would be beneficial; figure 4-30 shows a rivet design with a 9mm rivet head diameter, compared to the 7mm rivet head diameter used for this research. Many of the failures during tensile test of the previous rivet design occurred when the rivet lodged with the lower layer, and the rivet head pulled through the upper layer. This enlarged rivet head should reduce that mode of failure. A wider rivet bottom flange was the perpetual goal of rivet design, a 7mm wide bottom flange may prove to be impractical to insert into sheet metal, or it may penetrate with no more difficulty than the 6mm bottom flange, and produce a superior joint.



4-30. Potential rivet for further research

Due to the expense and time required to manufacture rivets by hand, not as many rivets were produced as could be desired. For further research it would be desired to have a rivet design more suitable for larger scale production, in order to conduct more extensive testing on the effects of process parameters such as spindle speed, and feed rate.

Occasionally during rivet insertion, the rivet and driver would develop a wobble, instead of the rivet penetrating straight down into the sheet metal the rivet would ‘walk’ in a circular motion during insertion. The effects of this can be seen in figure 4-31, to the right of the rivet in this figure is a partial void left behind from the rivet wobbling to the left and to the right during insertion.

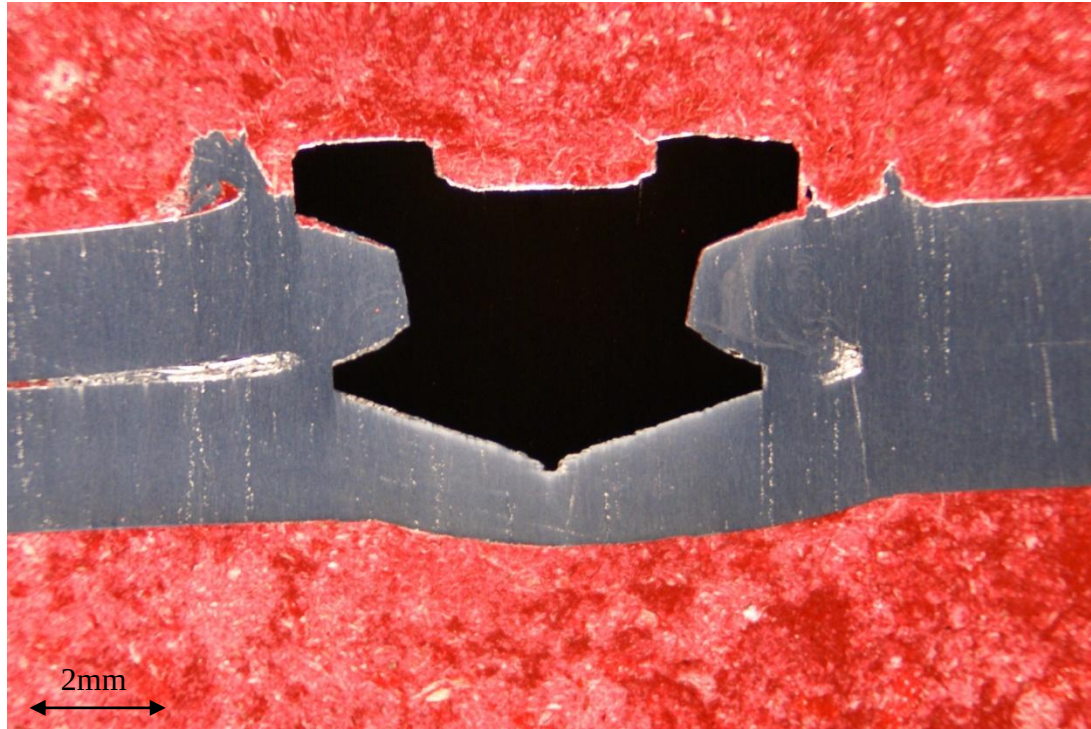


Figure 4-31. Rivet sample with partial void visible.

The severity of this ‘walk’ could be reduced by using a shorter driver that was thicker in diameter, in order to reduce driver deformation. A different solution to completely do away with insertion wobble would be to insert a roller bearing into the clamp itself. A roller bearing could be inserted into the circled area of the clamp as seen in figure 4-32; with a bearing in place the driver would be capable of traveling up and down, but would be prevented from moving in a circulation motion as was sometimes observed.

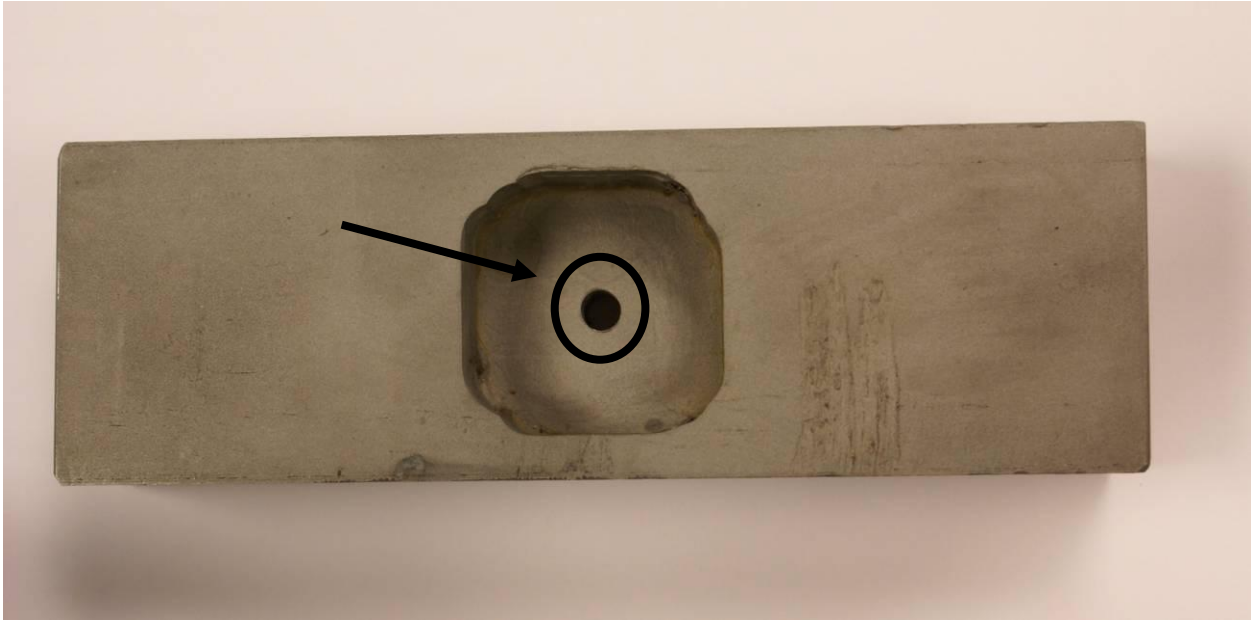


Figure 4-32. Potential location of rolling bearings

References

- [1] Y. Xu, Characterization of self-piercing riveted joints. Ph.D. Dissertations, The University of Toledo March 2006
- [2] Y. Durandet, R. Deam, A. Beer, W. Song, S. Blacket, Laser assisted self-pierce riveting of AZ31 magnesium alloy strips. *Materials and Design*. 31 (2010) S13-S16.
- [3] Osaka East Urban Area, Industry-Government-Academia Collaboration Project on FSW 2004 export-japan, Inc. http://www.mosaka.com/fsw/en/fsw/about_fsw.html
- [4] Hongyan Zhang and Jacek Senkara, *Resistance Welding: Fundamentals and Applications*. CRC Press/Taylor & Francis Group, 2nd edition, Boca Raton, London, New York. ISBN 978-1-4398537-1-9 (hardback), 978-1-4398537-2-6 (electronic). 2011. 656 pages, 360 illustrations.
- [5] S. Durbin, G. Ma W. Wang, A. Jayatissa, and H. Zhang, Friction-stir riveting-a new jointing method for Difficult-to Weld Metals, submitted to *Welding Journal*, Nov. 2011.
- [6] Z. Li, C. Hao, J. Zhang, and H. Zhang, 2007: Effects of sheet surface conditions on electrode life in aluminum welding, *Welding Journal*, vol. 86 (4), pp. 34 to 39-s.
- [7] B. Wang, C. Hao, J. Zhang and H. Zhang, 2006: A New Self Piercing Riveting Process and Strength Evaluation. *Transactions of the ASME, J. Manuf. Sci. Eng.*, vol. 128 pp. 580-587.
- [8] H. Zhang, J. Senkara, B. Wang, and Z. Gan, 2010: Self-piercing Riveting Al Alloys, 6th International Conference on Advances in Production Engineering(APE'10), 17-19 June 2010, Warsaw, Poland.
- [9] H. Luo, New joining techniques for magnesium alloy sheets, MS Thesis, Institute of Metal Research, Chinese Academy of Sciences, May 2008.

- [10] H. Luo, C. Hao, J. Zhang, Z. Gan, and H. Zhang, 2010: Characteristics of Resistance Welding Magnesium Alloys AZ31 and AZ91, submitted to Welding Journal, May 2010.
- [11] W. Lee, Y. Yeon, S. Jung. Joint properties of friction stir welded AZ31B-H24 magnesium alloy. *Materials Science and Technology*, 2003, 19(6):785-790.
- [12] S. Lathabai, M Painter, G. Cantin, and V. Tyagi. Friction spot joining of an extruded Al-Mg-Si alloy, *Scripta Materialia*, 2006, 55:899-902.
- [13] H. Seung, C. Park, Y. Sato, H. Kokawa. Effect of microtexture on fracture location in friction stir weld of Mg ally AZ61 during tensile test. *Scripta Materialia*, 2003, 49(2): 161-166.
- [14] Y. Sato, H. Seung, C. Park, M. Michiuchi, and Hiroyuki Kokawa. Constitutional liquation during dissimilar friction stir welding of Al and Mg alloys. *Scripta Materialia*, 2004, 50:1233-1236.
- [15] J. Esparza, W. Davis, L. Murr. Microstructure-property studies in friction-stir welded thixomolded magnesium alloy AM60. *Material Science*, 2003, 38(5):941-952.
- [16] A. Somasekharan, L. Murr. Microstructures in friction-stir welded dissimilar magnesium alloys and magnesium alloys to 6061-T6 aluminum alloy, *Materials Characterization*, 2004, 52(1):49-64.
- [17] H. Zhang and J. Senkara, *Resistance Welding: Fundamentals and Applications*. CRC Press/Taylor & Francis Group, Boca Raton, London, New York. ISBN 0-8493-2346-0. 2006. 431 pages, 300 illustrations.

List of Publications

1. H. Zhang, A. H. Jayatissa, S. Durbin, and G. Ma: *What if They Are Not Weld-able?* Management and Production Engineering Review" (MPER), a quarterly journal published by the Polish Academy of Sciences, submitted Oct. 2011.
2. S. Durbin, G. Ma, A. Jayatissa, and H. Zhang, 2011: *Characterization of Friction Stir Riveting Process*, submitted to Welding Journal, Nov. 2011.
3. G. Ma, S. Durbin, W. Wang, A. Jayatissa, and H. Zhang, 2012: *Performance of Friction Stir Riveted Joints*, to be submitted to Welding Science and Technology.
4. G. Ma, S. Durbin, W. Wang, A. Jayatissa, and H. Zhang, 2012: *Characteristics of Friction-Stir Riveted Joints*, 15th Sheet Metal Welding Conference, Oct., 2012, Livonia, MI.
5. S. Durbin, G. Ma, A. Jayatissa, H. Zhang, and J. Bohr, 2012: *Friction-Stir Riveting*, 15th Sheet Metal Welding Conference, Oct., 2012, Livonia, MI.
6. Poster: Feasibility Study of Hybrid Friction-Stir Riveting, A.H. Jayatissa, G. Ma, S. Durbin, and H. Zhang, 2011 National Science Foundation (NSF) Civil, Mechanical and Manufacturing Innovation (CMMI) Conference, held January 4-7, 2011 in Atlanta, Georgia.