

Feasibility Study on Dissimilar Materials Joint Made by Friction Stir Forming

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## Abstract

The need to join dissimilar materials is common to many industry sectors as the current demand is for the products of enhanced performance, reduced cost, weight reduction, optimized of properties or the tailored of the properties for specific applications. This paper is focused on studying the different joint structures made from different material combinations by Friction Stir Forming process. At present, joining Al to steel are successfully joined by this process, the present paper investigates the possibility of making strong joints from Fe-Al, Mg-Steel, as well as Aluminum to carbon fiber composites (Al-CFRP) material combinations.

The manufacturing industries are driven by using new lightweight material alternative to steel to form a thinner and stronger joint, which leads to a greater emphasis on the improvement of joining processes to allow interlocking formed by the material itself instead of using any rivets, bolts, adhesives, or any other mass addition. Friction Stir Forming is a relatively new process, which is an alternative to the mechanical fasteners. It is a process where the tool works heated materials into close contact, causing them to form a solid-state joint. No melting of materials occurs. Instead, the joint is formed by plastic deformation of the pieces. The previous part of the experiment is to define the important factors involved during the process, as well as the microstructure analysis on Al-Steel joint. Therefore, at this stage of the experiment, the joint made by Fe-Al, Mg-Steel, as well as Aluminum to carbon fiber composites (Al-CFRP) are studied.

Our study showed that friction stir forming process could be carried out over a wide range of operating parameters. It is a process where the shape of the joint could be changed according to the design of anvil. By changing the joint shape, the strength and

the quality could be affected. The friction stir forming joints are strong to satisfy the industry requirement. It is possible to form joints with lightweight materials using friction stir forming techniques. The material used to form the joint could affect the strength of the joint.

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# Chapter 1 Introduction

The market today requires more and more reliable and strong joint made from dissimilar materials, however, the formation of intermetallic phases within the joining zone will be formed simultaneously when joining dissimilar materials under high temperature. These phases cause a lack of the mechanical stability in the joining zone [Sepold, 2012]. The friction stir forming process has potential to form a joint without the intermetallic phases, because no melting is involved during the process. This thesis discussed the possibility to form a joint using friction stir forming (FSF) techniques. The tests were done on Al/Steel, Mg/Steel, Al/ CFRP, as well as Steel/Al material combinations.

## 1.1 Background

### *1.1.1 An Overview*

In recent decades, transportation industries have become pioneers in the use of lightweight materials such as aluminum alloys, other lightweight metals, and composite materials. The main purpose of this research is to find a better way to join the lightweight material than mechanical fasteners that adding extra weight. Aluminum alloy AA6014, GMW2 steel, and AZ31B-H23 Magnesium often are used for body structures and reinforcements in the automotive industry. For this reason Aluminum alloy AA6014, GMW2 steel, and AZ31B-H23 Magnesium were chosen as the sheet material in the study.

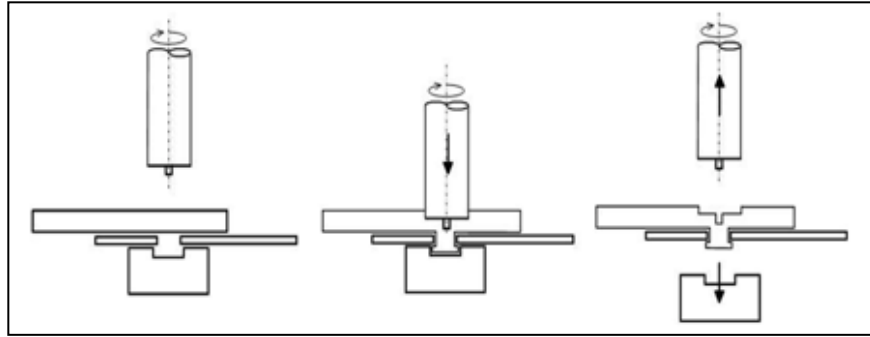


Fig. 1.1 FSF process [Lazarevic et al., 2012]

In the FSF process, two workpieces are clamped parallel on the machine table. A flat surface tool, which modified from friction stir welding (FSW) tool is plunged into the top workpiece. The tool is driven at moderate rotational speed (generally 1500-2500 rpm), brought into contact with the workpieces, which generates frictional heat, then driven under pressure into the workpiece until the material from the top workpiece penetrate into the predrilled hole on the bottom workpiece. The interlock is formed by the softened top sheet material by frictional heat.

The FSF process is a relatively cheap process, since it does not require any additional rivets, bolts, or additional electrodes. It is an environmentally friendly process with no fumes, unsightly soot, shielding gas, spatter, and ultraviolet light. This is a quiet process which will save the manufacture's cost and also save the environment.

### ***1.1.2 Motivation***

The use of lightweight materials is driven largely by their role in achieving greater energy efficiency. Also, lighter weight creates the potential for additional capabilities or resources to be added to the platform. The availability of advanced lightweight materials is thus a crosscutting requirement that is crucial to improving

the performance of many systems in defense, energy, transportation and general engineered products [DPAC, 2013]. Moreover, lightweight materials have additional applications in areas such as wind turbines; medical technology, pressure vessels and they could provide more alternative energy sources.

Composite materials, nowadays, can be considered a valid alternative to metal, providing excellent mechanical performances with very low values of density. Their use has spread visibly in the last years in different areas such as transportation industries but also top-level sport applications.

In this research, the possibility of forming a strong joint by using the lightweight materials is investigated. The strength of the joint formed need to be improved compare to the traditional adhesive joint. The comparison of the traditional joining process and FSF is addressed in this paper.

## **1.2 Literature review**

### ***1.2.1 Available technologies***

Automobile industries are interested in joining aluminum and magnesium alloys because they are recognized as lightweight structural materials with high performance and efficiency. However, steels are still widely used for structural components because of their high absolute strength and good cost efficiency. Hence, it is becoming very important to join thin Al or Mg sheets to thin steel ones to fabricate structural components [Uematsu et al., 2012]. The main goal of dissimilar material joining is weight reduction, optimization of properties or the tailoring of the properties for specific applications in combination with an efficient joining technology [Sepold et al, 2008].

There are a few technologies commercially available in the market for dissimilar material joining. Laser beam welding (LBW) is a versatile process capable of welding carbon steels, HSLA steels, stainless steel, aluminum, and titanium. Due to high cooling rates, cracking is a concern when welding high-carbon steels. However, LBW is an expensive process [Schwartz, 2011]. Researchers at the University of Michigan have developed self-piercing rivet to join dissimilar materials, in particular, for joining aluminum, magnesium, composite, and plastic components to steel components. The rivet pierces and passes through the non-ferrous component and into contact with the ferrous component to form a mechanical interlock [Hu, 2013]. Clinching is a mechanical joining method, especially for sheet metal parts. The process is perceived as being a simple method that is based on only the accurate movement of a punch into a die. During the process, sheet metals are deformed locally without the use of any additional elements [Varis, 2006]. Friction assist clinching is a relatively new technique where the tool is contacting a punch to stacked workpieces and rotating the punch to generate frictional heat in the workpieces, and advancing the punch into the workpieces to form a mechanically-interlocking joint [Carter, 2010].

This study focuses on joining of dissimilar materials by friction stir processing. The welding institute (TWI) investigated friction stir welding (FSW), where the tool follows a linear motion alongside the workpiece, and heating is created within the workpiece both by friction between the rotating tool pin and shoulder and by severe plastic deformation of the workpiece. Further, because FSW does not involve the use of filler metal and also there is no melting, any aluminum alloy can be joint without concern for compatibility of composition or solidification cracking [Rajiv, 2007].

Recently, a friction stir spot welding (FSSW) technique has been invented by Mazda Motor Corporation and Kawasaki Heavy Industry [Mazda, 2003]. FSSW, similar to FSW, the Spot Welding process also consisted of light materials as aluminum on an industrial scale as presented by Karosseriebau et al. [2013] from Stirzone. FSSW uses, like FSW, the deformation caused by the heat from friction and stirring of the material due to the rotation and penetration of the welding tool in the overlapping plates to be welded. The majority of the FSSW joint are made from die steel (AISI-H13) when joining aluminum alloys, and tungsten-based and nickel based superalloy tools are used when joining steels. The tool pin typically has one or a combination threads, spiral terraces, flat sides, or flutes, which promote mixing of upper and lower sheet materials during the welding operation [Mustafa, 2008]. When joining Al alloy to zinc-coated steel, the lower steel is not penetrated by the solid-state diffusion bond between the upper aluminum sheet and the zinc coating [Gendo et al., 2007]. FSSW technique plays an important role in welding magnesium because it can provide great welding efficiency, low input, little energy consumption, pollution free work environment and a good joint with lower thermal deformation of the workpieces and higher mechanical properties of the welded joints [Shen et al., 2012].

Instead of two-sided access for self-piercing riveting, friction stir blind riveting (FSBR) could be done for one-sided joining. In FSBR a blind rivet is driven at high rotational speed typically 6000–12,000 rpm and brought into contact with the workpieces, thereby generating frictional heat between the rivet and the workpiece, which softens the workpiece material and enables the rivet to be driven into the workpieces under reduced force. Once fully inserted, the blind rivet is upset using the internal mandrel as in normal

blind riveting to fasten the workpieces together. Friction stir blind riveting thus eliminates the need for the separate hole making operation required in the conventional blind riveting process while retaining the advantage of one-sided accessibility [Gao, 2009].

### *1.2.2. Different Setups and conclusions from similar research*

Uematsu [2012] from Gifu University has compared the fatigue behavior between Al alloy A6061 /steel joint and Mg alloy AZ31/steel joint made by FSSW. The research has proved that the material flow in the nugget of the Mg/steel weld was less than that in the Al/steel one. The Al/steel weld exhibited higher static tensile–shear strength than the Al/Al weld, while the strengths of Mg/steel and Mg/Mg welds were comparable. Tensile–shear fatigue tests were performed using lap shear specimens of both dissimilar and similar welds. The dissimilar welds exhibited nearly the same fatigue strengths as the similar ones. The Al/ steel dissimilar weld has a higher static and fatigue strengths, which could be attributed to the high proof stress of the Al alloy and the larger effective nugget size of the Al/steel dissimilar weld. Due to an overlap-welding configuration, a weld made by FSSW shows a distinct macrostructure [Badarinarayan et al., 2009]. Yang [2010] from Hitachi America proved that flow transition zone, stir zone, and torsion zone are developed in the welds due to the combination of rotational, horizontal and vertical motions of the plasticized material. It is believed that the intrinsic driving force for the downward motion of the plasticized material is originated from the material release from the rotating pin through an outward-spinning motion.

This literature review shows that there has been research into dissimilar material joining, and this is a growing area of interest. However, there is a lack of research about

dissimilar material joining by the new FSF technique, which becomes the goal of this study. FSF is a process where the tool works heated materials into close contact, causing them to form a solid-state joint. During the process no melting of materials occurs, instead, the joint is formed by plastic deformation of the workpieces. It is an alternative to the mechanical fasteners.

### **1.3 Research Issues and Thesis Organization**

In an effort to better evaluate the capabilities of this process, particularly its capabilities when compared with processes in current use, and the joints produced using it, this study was conducted to compare FSF joints with traditional joining process.

#### ***1.3.1. Feasibility of Different Material Combinations***

Aluminum and steel pieces were used in past research. The optimal condition for forming a joint was investigated during previous research. The previous part of this research was focused on exploring the feasibility of concept and finding the optimal values of the important parameters such as spindle and plunge speed, torque, geometrical dimensions of the tool.

However, there is still a major question about the range of materials possible with the FSF process and also the strength that individual joint could reach. The possibility of the formation of the joint need to be fully discussed. FSF is a relatively new technology, where the strength of the joint need to be evaluated. The strength of joint formed from different materials is compared with each other sets. The strength of the joint formed by FSF is compared with the joint formed from other traditional methods too.

### *1.3.2. Effect of Experimental Setup and Process Parameters on FSF Process Feasibility*

Part of the previous experiment was done in General Motors Technical Center located in Warren, Michigan, where the machining setup is similar to the friction stir spot welding process. The part of this project is to adjust the current process for industrial conditions, where the size of the workpieces, the fixture used, and also the shape of the anvil need to be designed to meet the industrial conditions. In order for that to be satisfied, improving and understanding the difference in setup for different materials used during the process, and also the factors that will affect the final results when preparing the materials. The samples made by different combinations of materials are tested using the lap joint testing.

It is thought that the FSF setup will vary depending on the type of material and the combination of materials. More specifically, the setup will have a significant effect on the success for the different material combinations. A joint made between carbon fiber reinforced nylon and aluminum will require a different setup than aluminum to steel. A joint made with steel sheet on top of aluminum will require different setup than aluminum on top of steel. This research will investigate the effect of the experimental setup on the feasibility of the joining process.

## **Chapter 2 Feasibility study on friction stir forming of different materials**

### **2.1 Introduction**

This chapter is focused on the properties of the materials used in this experiment as well as the different CNC machining setup for dissimilar materials combinations due to the material properties. The first goal of this research was to produce a good quality joint with dissimilar material groupings by using CNC. FSF is a relatively new process. Therefore, FSF must be thoroughly analyzed experimentally to find the suitable machining setup for dissimilar lightweight materials in order to form a durable joint with less intermetallic regions.

At first, the properties of the material are studied, with the intent to find the right material combination, along with the alignment of the workpiece. There are two major experiment setups for the process to fit the appropriate material groupings, Predrilled holes on the bottom workpiece or predrilled ring holes on the top workpiece. The diameter of the ring holes on the top workpiece is studied. Through the entire process, the tool centering, the bottom workpiece hole and top workpiece ring-holes' position were tremendously important.

It is believed that the joint made by stronger material should have stronger mechanical property. One of the objectives of this experiment is to use the harder material as top plate. After applying frictional heat, the harder material starts to penetrate into the bottom plate, where the flowing of the harder material makes the joint. Ultimately, a stronger joint will be created. Similar to high-speed metal cutting, when the

tool rotates on top of the harder material the temperature increases tremendously by frictional heating and chip deformation, and also it is an extreme contact condition.

## **2.2 Material properties of coupons**

The main purpose of this experiment is to study the possibility of making strong joints from Steel-Al, Mg-Steel, as well as Aluminum to carbon fiber composites (Al-CFRP) material combinations.

Traditionally, the soft material needed to be positioned at top, in order for it to soften and penetrate the predrilled hole on the bottom plate. However, to increase the strength of the joint, the joint is preferably formed from the stronger material. One of the ultimate goals of this experiment is to form joint with stronger material without damaging the weaker material.

### **2.2.1 GMW2 Steel**

GMW2 steel has a layer that provides a durable surface and good corrosion resistance. This layer is made from hot-dip galvanizing (HDG) process. This process involves impregnation of molten zinc to the steel to create a Fe - Zn bath mixtures. In short galvanized, a couple seconds in duration, diffusion makes an intermetallic compound. This compound is an excellent combination between the zinc coating and steel. Iron and zinc react in the steel, forming a series of zinc - iron alloy layer, usually made with pure zinc. The galvanization is possible because of the relatively low melting point of zinc (419.58 °C) [GM, 2010].

### 2.2.2 1010-1018 Steel

Low carbon steels contains up to around 0.2 percent carbon by weight. The automotive industry employs considerable amount of low carbon steel, as it is moderately easy to form. For instance the roofs, hoods, doors, and body sides on regular automobiles are also usually made from low carbon steel. Other automobile parts, such as spare tire tubs and dash panels feature are low carbon steel construction too. Some of the more widely used low carbon steels include 1010, 1018, and 1020 steel.

The thicker steel coupons are made from general-purpose low carbon steel, which has minimum yield strength of 30,000 psi. The detailed chemical composition is listed in the table below.

Table 1 The chemical composition of low carbon steel coupons[AISI handbook,2013]

Steel	Carbon	Manganese	Silicon	Phosphorus	Sulfur	Chromium	Molybdenum	Vanadium	Other
1010-1018	0.13-0.20%	0.30-0.90%	0.15-0.30%	0.04%Max.	0.50%Max	None	None	None	None

### 2.2.3 6014 Aluminum

Aluminum association recently reported that Aluminum has surpassed iron as the second most prevalent automotive material, with an average 144kg per vehicle in North America. The most commonly used aluminum alloys in automotive industry are AA5083-O, AA5182-O, AA5754-O, AA6014, AA6022, AA6063-T6, AA6111-T4, AA6016-T4, and AA7075. 6XXX series aluminum alloy contains magnesium and silicon, and they are heat treatable. Most of the automotive industries used 6XXX series aluminum alloy for inner and outer body applications.

Aluminum has lower formability and strength than steel, but with a higher material cost. Aluminum alloys become one of the most popular lightweight material used in automotive applications is because of its corrosion resistant. As well as the dent resistance, energy absorption and crash resistance of aluminum panel are less than those of a steel panel. Table below shows the composition of Al coupons used in this experiment.

**Table 2 The chemical composition of AA 6014 coupons [ASM, 2012]**

	Al	Cr	Cu	Fe	Mg	Mn	Other, each	Other, total	Si	Ti	V	Zn
AA6014	≤97.0	≤0.20	≤ 0.25	≤ 0.35	0.4 - 0.8	0.05 - 0.2	≤ 0.050	≤ 0.15 %	0.3 - 0.6	≤ 0.10	0.05 - 0.2	≤0.10

#### **2.2.4 PA66, Carbon Fiber**

The carbon fiber industry is growing with steady increasing demand from aerospace, automotive and defense markets as well as smaller markets such as sporting goods and construction material. The airbus A380 jetliner and the Boeing 787 Dreamliner have accelerated the growth in global CF demand to approximately 22,679 tones per year [Hexcel Corp, Aerostrategy, 2013].

The DOE has major effort to develop a high throughput manufacturing process for carbon fiber material, which means that the industry should be able to join a carbon fiber material with other materials, such as steel, aluminum, and magnesium.

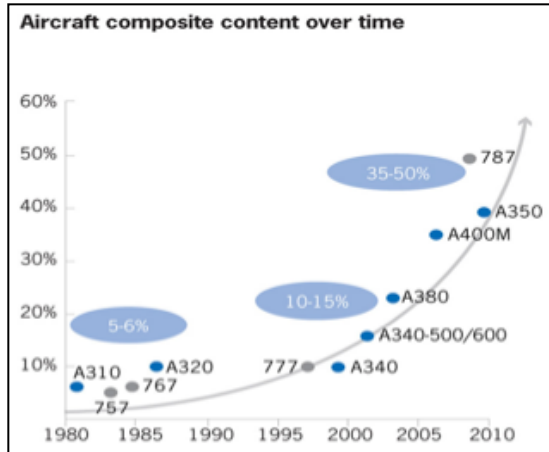


Fig. 2.2 Aircraft composite content over time [Hexcel Corp, Aerostrategy, 2013]

For this experiment, two carbon fiber composites are used for testing the possibility to form a joint. One is carbon fiber reinforced nylon, which contains 40% carbon fiber, as well as nylon composite, as described in Table 2.3.

Table 3 Properties of carbon fiber PA66

Property	Description		PA66, carbon fiber
	Method	Units	NN-40CF/000 BLACK
Specific gravity	ASTM D792	--	1.32
Molding shrinkage - flow	ASTM D955	in/in	0.001-0.002
Tensile strength, yield	ASTM D638	psi	36000
Tensile elongation, break	ASTM D638	%	3-1
Flexural modulus	ASTM D790	psi	3,000,000
Flexural strength	ASTM D790	psi	55,000
Izod impact, notched, RT	ASTM D256	ft-lb/in	2
HDT, 264psi, unannealed	ASTM D648	deg F	500
Surface Resistivity (Ohm/Sq cm.)	PolyOne	Ohm/sq.	1.30E+03

The other CFRP used for this experiment is CFRP with epoxy coating. The epoxy matrix is a polymer resin, which is used to bind the reinforcements together.

### 2.2.5 AZ31B-H23 Mg

The international magnesium Association predicts that the use of magnesium will grow steadily by roughly 5-7% from the current 4.5-5.4 kg per vehicle. The magnesium used for this experiment is AZ31B-H23, which usually used in automotive industry. The chemical composition and mechanical properties of the magnesium are listed below.

**Table 4 The chemical composition of AZ31B-H23 coupons [MENA Products Standards]**

	Al	Zn	Mn	Ca	Cu	Fe	Ni	Si	Others Each	Others Total	Mg
<b>Minimum</b>	2.5	0.7	0.20	---	---	---	---	---	---	---	---
<b>Maximum</b>	3.5	1.3	1.0	0.04	0.05	0.005	0.005	0.05	0.10	0.30	Balance

**Table 5 Mechanical property Determinations [MENA Product Standards]**

MENA Lot	Testing Direction	Ultimate Tensile Strength KSI (MPa)		Tensile Yield Strength KSI (MPa)		Elongation in 2 <sup>o</sup> or 4 Diameter	
		Minimum	Maximum	Minimum	Maximum	Minimum	Maximum
21658	Longitudinal	39.3(271)	39.5(272)	27.1(187)	28.0(193)	23.2	24.8

## 2.3 Pretreatment of the sample plates

FSF is a process where the tool works heated materials into close contact, causing them to form a solid-state joint. In FSF, the motion of the tool is usually limited to a vertical movement of plunging and retreating after a possible dwell time. The tool stirs on top of the aluminum coupon and plunges down at the same time.

The softer material is penetrated into the predrilled hole in the harder material workpiece. At the same time an interlock with neck and head is formed, which will form the joint. The neck and head shape is necessary to keep the joint strong.

### *2.3.1 Single-hole sample*

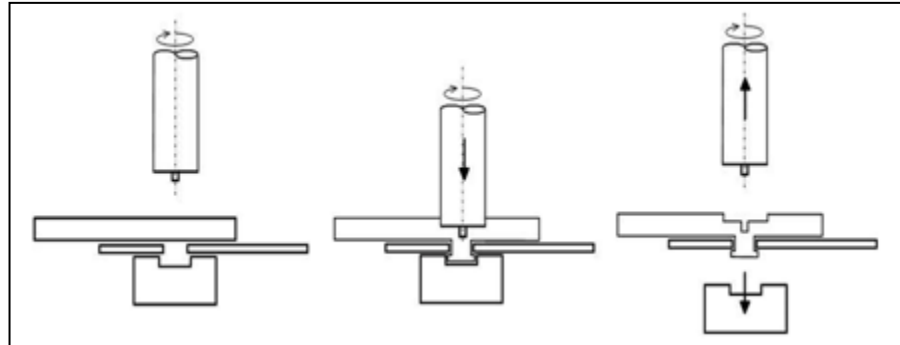


Figure 2.3 Steps of the FSF process [Lazarevic et al., 2012]

The samples were 5” x 1.5” and had a pre-drilled hole. The hole was placed on end of the sample, 0.75” away from the sides.

### *2.3.2 Ring-hole sample*

In attempt to form an interlock and improve the strength of the joint between the aluminum and the carbon fiber composite, perforations of 2 mm diameter were drilled in a circular pattern around the joining area in the aluminum sheet to allow the softer material from bottom plates to infiltrate into these holes. The diameter of the circular pattern is determined by the diameter of the tools. A photograph of the aluminum coupon with the holes drilled in.

## 2.4 Design and Material properties of tools



Figure 2.4, left: Si<sub>3</sub>N<sub>4</sub> tool, right: H13 steel tool

Two different tools were used; both of whose surfaces were flat. The material used for Tool A is silicon nitride, which had a diameter of 11.47 mm (Figure 2.4). Ceramic tools, for instance, silicon nitride (Si<sub>3</sub>N<sub>4</sub>) tools are unique materials to withstand such extreme thermo mechanical loading [Gomes, 1999]. The other reason that drives us to use the silicon nitride tool is that high-temperature applications of ceramics tools necessarily exclude the use of conventional lubricants.

## 2.5 Experimental Setup

Figure 2.5(a) shows the set up in the CNC machine.



Fig. 2.5: Setup of CNC FSF experiments (a) Setup in CNC with measurement equipment (b) close up view of tool and fixture [sladjan, 2013]



Fig. 2.6 Close up view of set-up

### *2.5.1 Coupons and Fixture Setup*

The coupons were placed in a specially designed fixture showed in Figure 2.3(b) with a 25.4 mm overlap. A dynamometer was placed under the fixture to monitor the axial load and the applied torque during the joining process.

### *2.5.2 Design of Anvil*

The purpose of designing an anvil with different geometry for the uppermost surface is to improve the strength of the joint by changing the shape of the joint. In other words, the new shape of the anvil will direct the flow of the softened material to form an intended interlock. Three different geometry anvils are used for this experiment, anvil with flat surface, anvil with single hole (Figure 2.7a), anvil with raised pin in the center (Figure 2.7b).

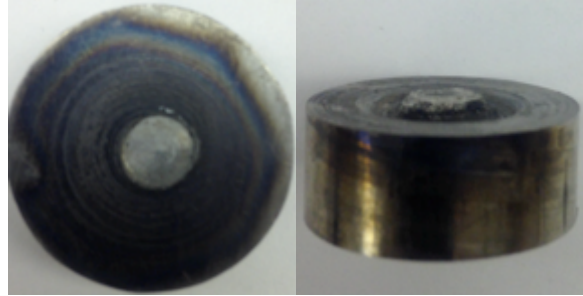


Fig. 2.7 Photograph of different anvils (a) anvil with single hole (b) anvil with raised pin

The flat anvil is used for the sample prepared with ring hole, where the bottom material with lower melting point will penetrate into the ring holes. In this case the geometry of the anvil will not affect the formation of the joint. The anvil with single hole drilled in the center is used for formation of a single pin interlock. Most of time this anvil is used for top coupon made with softer material.

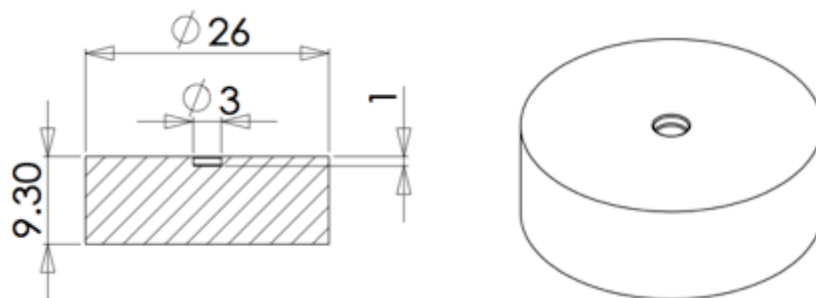


Fig. 2.8 Schematic drawing of the single hole anvil

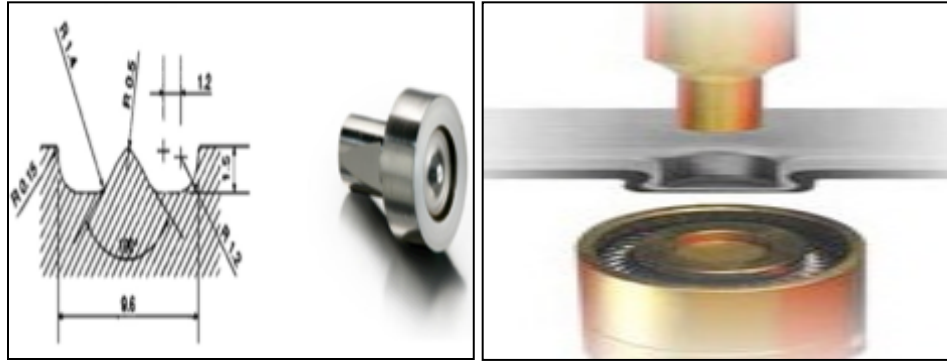


Fig. 2.9 (a) Rivet spot setting tool die (b) Die used for clinching

The inspiration of designing the new raised pin anvil was from spot setting tool die for rivet process as well as the die used for clinching process. As shown in the figure below, a raised pin with slope is machined from a rod with a flat surface by using lathe.

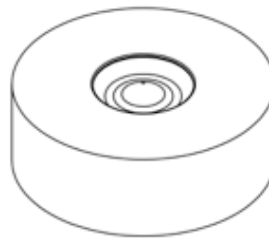


Fig. 2.10 Schematic of the anvil with a raised pin

### 2.5.3 Data Acquisition

Measuring the axial force and torque, four-component Kistler 9272 dynamometer was used. The force gauge can measure the axial force of up to 20 kN, which is sufficient axial force to satisfy the maximum normal operation 7 kN experiment. Operating temperature range of the instrument is from zero to 70 °C. Coupon temperature becomes

much higher than 70 °C during machining, the anvil and the fixture were functioned as a media for heat insulation.

The dynamometer was connected to a dual mode charge amplifier Piezotron (Kistler model 5010). The signal generated by the dynamometer was sent to the amplifier in voltage and been collected by Labview software. Finally, the data was plotted in an excel file.

#### *2.5.4 Lap Joint Shear Strength Testing*

After joining, the joined specimen was about 175 mm long. Tensile shear tests were conducted with the joint formed from different material combinations on an Instron tensile testing machine at a constant crosshead speed of 3 mm/min. The failure load recorded for each test was used as an indication of the joint strength. The failure mode of the joint formed by friction stir forming process could be categorized into three types. [Sladjan, 2013] These failures occurred during the previous testing too. Failure mechanism can be divided into three types. However, most of the sample is not purely one way to fail. After the testing, these three types were found and defined from the previous experiment. The same failure modes happened on the joints formed with different material combinations, which proves the failure modes of the FSF process.

Toughness is also defined as area of stress-strain diagram. Toughness is related to the area under the stress-strain curve. In order to be tough, a material must be both strong and ductile. For example, brittle materials (like ceramics) that are strong but with limited ductility are not tough; conversely, very ductile materials with low strengths are also not tough. To be tough, a material should withstand both high stresses and high strains.

Generally speaking, strength indicates how much force the material can support, while toughness indicates how much energy a material can absorb before rupturing.

$$U_T = \text{Area underneath the stress-strain } (\sigma\text{-}\varepsilon) \text{ curve} = \sigma \times \varepsilon \quad (1)$$

$$U_T = J \cdot m^{-3} \cdot 10^4 \quad (2)$$

## 2.6 Experimental Procedure

One of the most important procedure for this experiment is to align the axis of the tool, holes on the coupons, and the cavity or pin of the anvil. Centering need to be done for each of the experiment. One of the easiest way to maintain an accute centering is to mark the invisible anvil hole or pin on the fixture, this will increase the accuracy and consistency of the experiment. However, it was still difficult to remain a high accuracy and consistency in the process, because of the moving of the workpiece when securing the coupons onto the fixture using fasteners. The tesitng coupons are placed in the prepared cavity to secure the Y axis movement. The Z axis movement is secured by a top plate which was carefully placed on top of the aligned two coupons, as shown in Fig. 2.11. All of this had to be carefully done so the components did not get misaligned, especially the coupon with the holes.

Before each of the CNC machining, it was necessary to set the zero for all three directions. After the entire coupon installation was completed, the vertical tool position had to be zeroed in the following way. The zeroing for Z direction need to be done by using an optical tool length setter when the thickness of the coupons were changed.



Fig. 2.11 Optical tool length setter

With a precise centering and zeroing, the CNC was started by following the command from the g-code program. The g-code program was loaded to the CNC previously before the start of the machining. The time taken for the entire process is depending on the feed rate and plunge depth. However, generally it was less than 20 seconds. Since the whole process was operated without coolant, the temperature of the completed sample was high, it is necessary to allow a cooling time before the labeling time.

## Chapter 3 Experimental Results

As mentioned in chapter one, the tests were done on Mg/Steel, Al/ CFRP, Steel/Mg as well as Steel/Al material combinations. Different setups were applied to different material combinations. One of the major results will be the possibility of forming a joint. Moreover the strength of the joints formed by different material combinations with different setups was recorded, and also from the curve we could get the amount of energy this joint can absorb before rupturing. The final results were compared to the strength and toughness formed from the same experimental setup but different material combinations to verify the quality of the joint. For instance, the Steel/Mg combination and Steel/Al combination, with the  $\text{Si}_3\text{N}_4$  tool and raised pin anvil were compared. On the other hand, the same material with different experimental setup was compared to establish a superior experimental setup. For instance, the Mg/Steel joint made with the single pin anvil and the raised pin anvil were compared. Finally, the relationship between material properties and joint strength formed was exposed in this section too.

### 3.1 Aluminium and steel combinations

In order to form a joint with the harder material flowing into the cavity, at this stage of experiment, 1.45mm low carbon 1010-1018 Steel coupon was placed on top of the 1.4mm AA6014 Aluminum coupon. A different experimental setup was used to prevent the softer aluminum coupon melt before the steel flow into the cavity to form an interlock. The first trial to form a joint with steel coupon on the top of aluminum coupon with a predrilled hole was failed. The GMW2 steel was not “flowing”, instead, the bottom plate aluminum with a hole was affected or stacked together with the top plate, which is

inclined to a traditional fusion bonding process. In order to form a strong friction forming joint, a thicker steel plate was applied as well as a new design of anvil was made to prevent the bottom aluminum melt. The new anvil with a raised pin was designed for this particular joint, as shown in Chapter 2. The purpose of designing this anvil was to make sure the softened steel would form a shape similar to a clinching joint without touching the bottom aluminum plate. Figure 3.1 below shows the basic experimental setup.

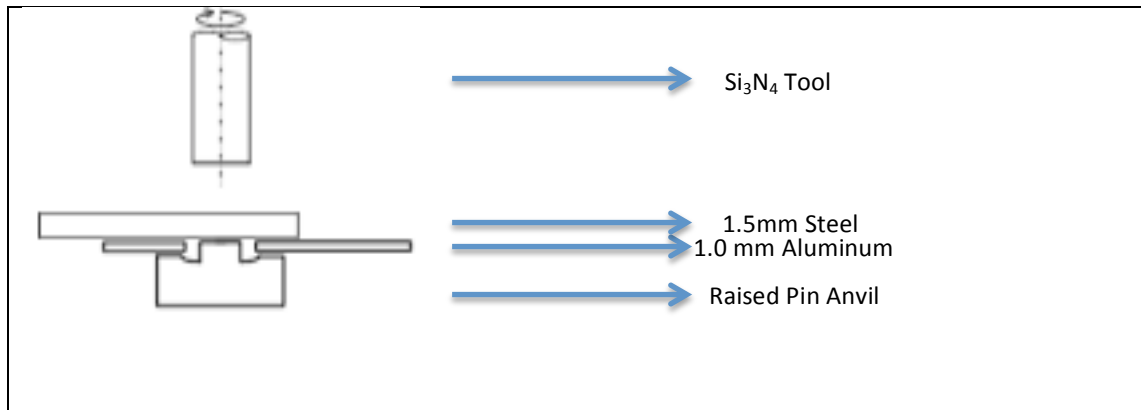


Fig. 3.1 Basic machining setup for Steel/Al combinations

The plunge depth for this trial was 1.9mm, 2.0mm, and 2.1mm. The feed rate was fixed at 7mm/min, the spindle speed is maintained at 3500rpm for this sets of testing samples. As shown in the figure above, the strength of the joint is approximately 3500-4500N. The axial force and torque from the dynamometer is about 6kN for this sets of samples.

As predicted, an interlock similar to clinching joint was formed after the machining, where the deformed steel penetrated into the anvil and formed a mechanical interlock. It is observed that during the machining only the steel was softened and deformed. Even though the aluminum has a lower melting temperature, it was not deformed or affected

besides a little wear off on the contact surface, shown in figure 3.2 (b). This means the material of the produced interlock is deformed steel. The joint formed by the harder material low carbon steel was expected to have a higher joint strength than the joint formed by the softer aluminum material, to prove this a lap shear strength testing was performed afterwards.

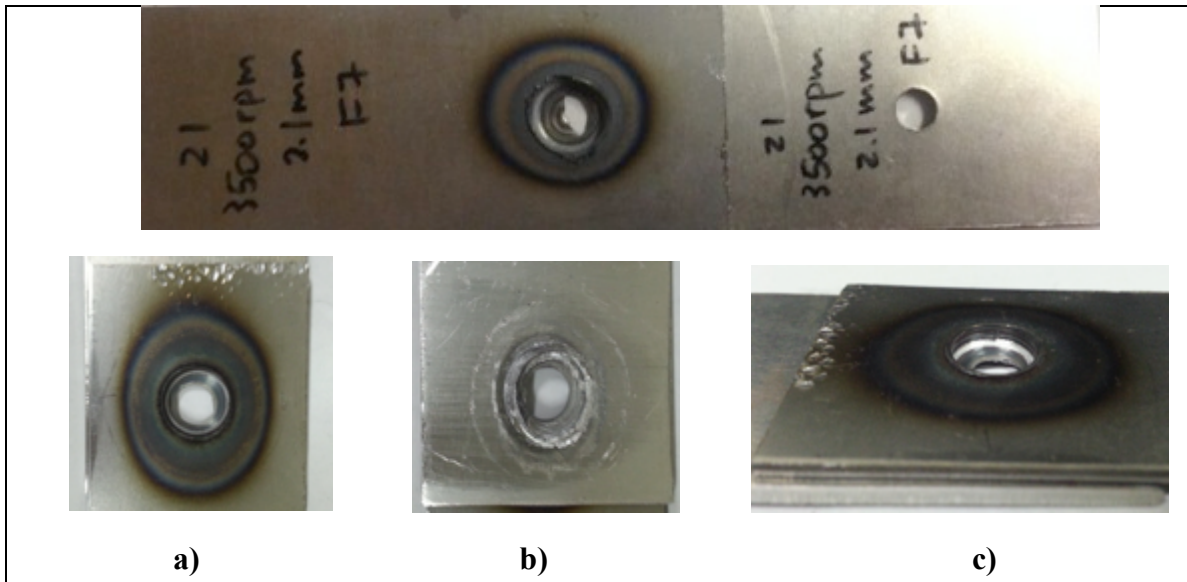


Fig. 3.2 Photograph of the joint formed a) top view [steel side], b) bottom view [aluminum side], c) side view

The appropriate dimensions for the clinching rings of the formed joint are 13.00mm for the outer diameter and 9.00 mm for the inner diameter. The average height of the clinching ring was about 1.10 mm. The dimensions obtained conforms the design of the anvil as shown in the figure below.

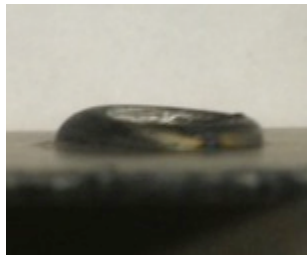
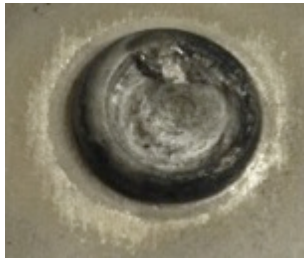


Fig. 3.3 Formed clinching joint with raised pin anvil

A tensile shear testing was implemented after the joint formed. The failure mode of this joint is neck shear. In this case, the specimens pulled on the lap-shear strength machine would fail in their weakest point, the neck. [Slandjan, 2013]

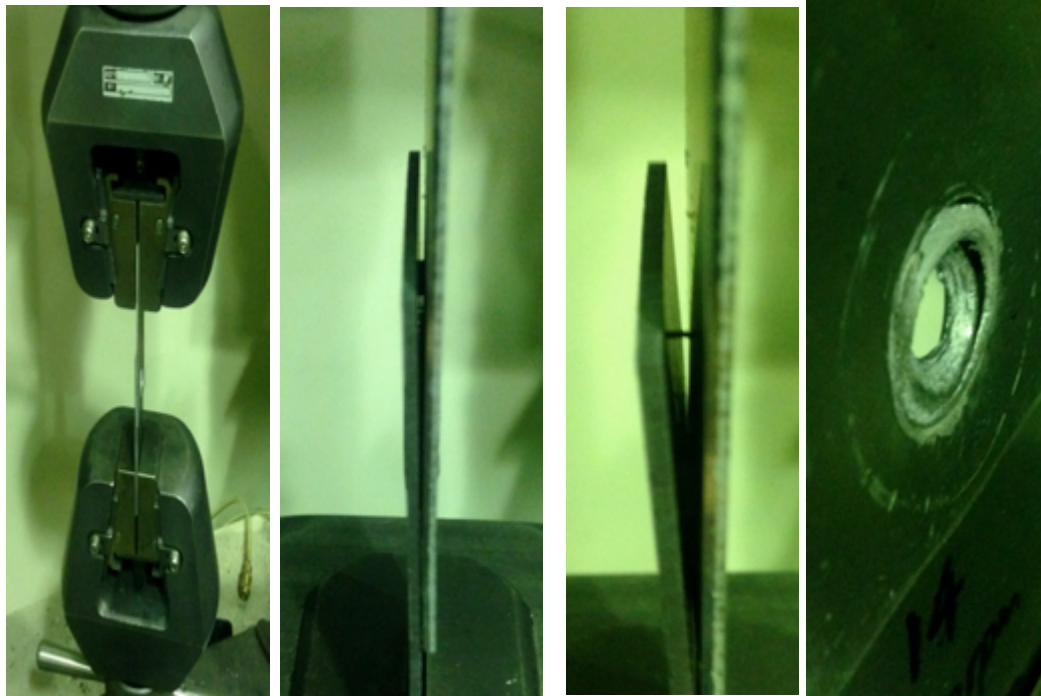
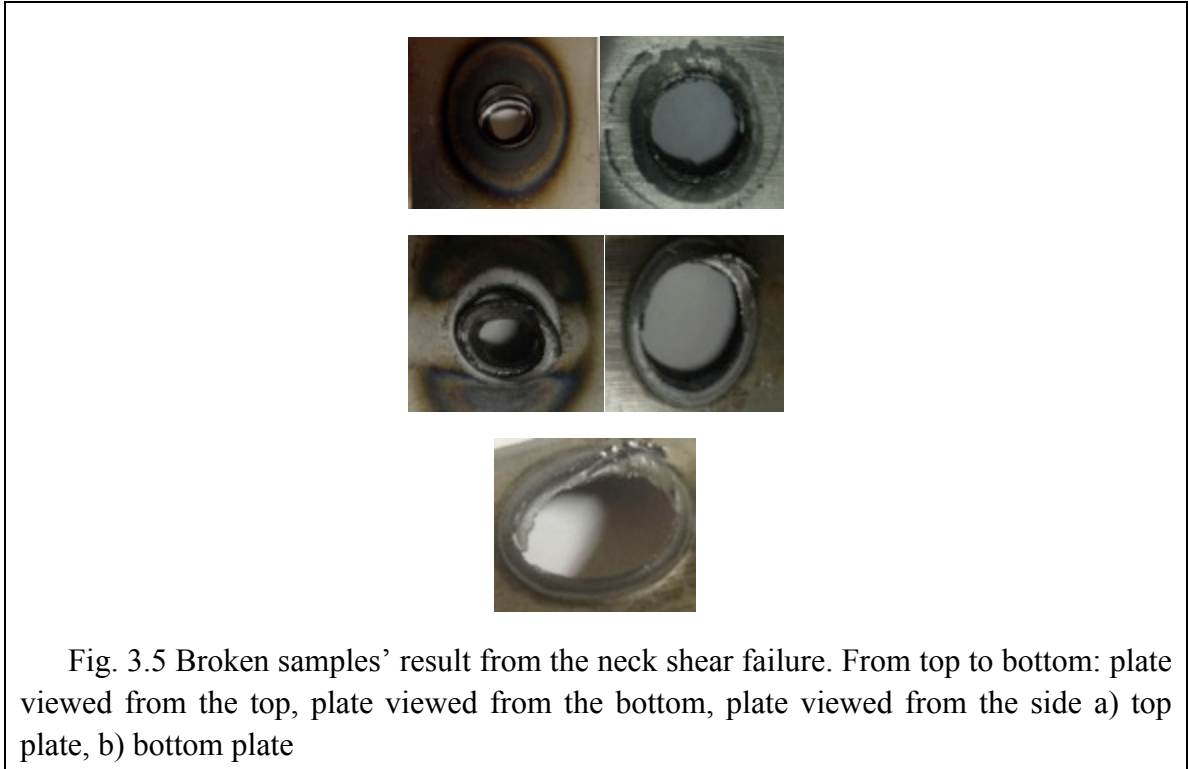


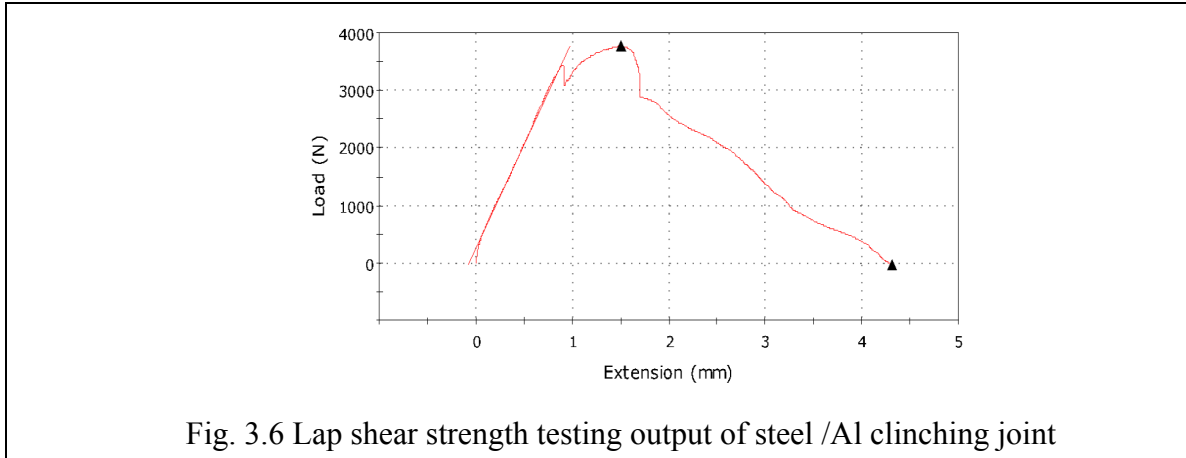
Fig.3.4 Steps for Steel/Al joint failure Bottom coupon: Steel, Top Coupon: Aluminum

As shown above, the bottom steel coupon start to bend, and the thinnest part of the joint, which is in the center of the formed joint start to crack, at the same time a gap between the two coupons is initiated. As the load increasing, the aluminum start to peel

off from the joint, and aluminum coupon start to bend. The formed clinch joint destroyed part of the aluminum right before the joint completely failed. Eventually the joint failed.



As shown in the figure above, most of the samples formed by Steel/Al combination were failed at the neck of the joint, which is the weakest point of the joint. The clinching joint part failed. During the tension test, the steel joint started to break off from one side of the joint. Once the joint started to destroy a sudden drop could be observed from the stress strain curve. However, another 3mm extension is needed to completely destroy the joint from the starting point. The strength of this joint shows that this new machining setup is applicable to automotive industry.



The strength for the joint formed by Steel/Al combination is 3500-4500 N from the average results of 8 samples. By using the same parameters, the average strength of the Al/Steel combination was 4000 N, which indicates that the joint could support 4000 N of force before it starts to fail.

During the process, the joint has absorbed energy before rupturing. The larger the energy the tougher the joint will be, which is a number to justify the quality of the joint. From the area under the curve, we could conclude that this is a tough joint, which would be able to ensure the safety for the joint made by this setup.

The joint strength was about 4kN. It is compared to the joint formed by the FSSW process, which is about 1.6kN [Caroline, 2013]. This shows that the joint formed with this method has a stronger joint, which is more practical than FSSW joints.

### 3.2 Magnesium and steel combinations

For the Mg and steel combination, two different setups were tried to see the possibility of the joint, due to the material properties differences between Aluminium and Magnesium. The similar setup as the Al/Steel was tried for Mg/Steel, another setup with

the new anvil was tested with the same materials. From the results obtained in this section, we could conclude how joint properties will be affected by the material properties by comparing the joint formed from Al/Steel.

### 3.2.1 Mg/GMW2 steel

The Magnesium and steel combination had the same setup as Al/Steel combination, where Magnesium was the top coupon and steel was the bottom coupon. In order to maintain a consistency for the experiment results, the tool used for the magnesium and steel combination was  $\text{Si}_3\text{N}_4$  Tool. A 1.7mm Magnesium was used as the top coupon, and 0.7mm GMW2 steel coupon with a pre-fabricated hole with a diameter of 2.54mm was used for the bottom coupon.

For this experiment, the same experimental setup as the Al/Steel combination, and optimum parameters attained from the Al/Steel combination were used to form the joint. The figure below shows the basic machining setup for Magnesium and steel combinations.

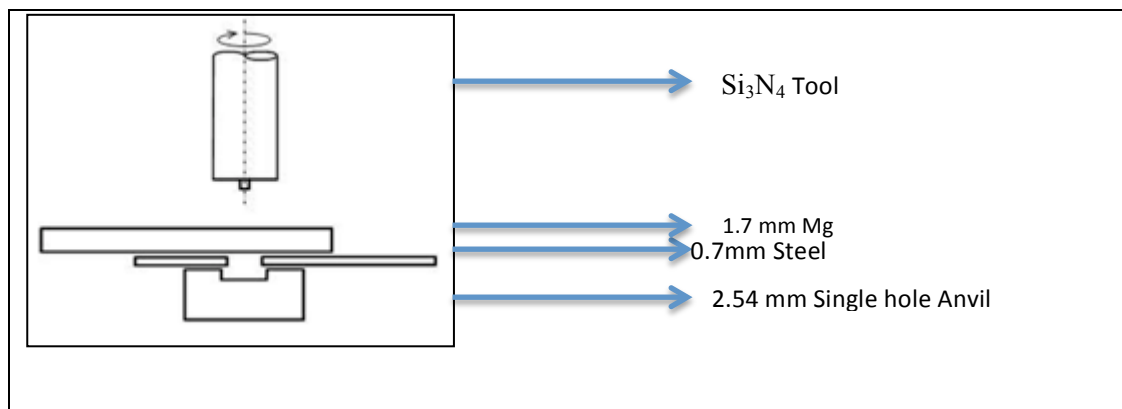
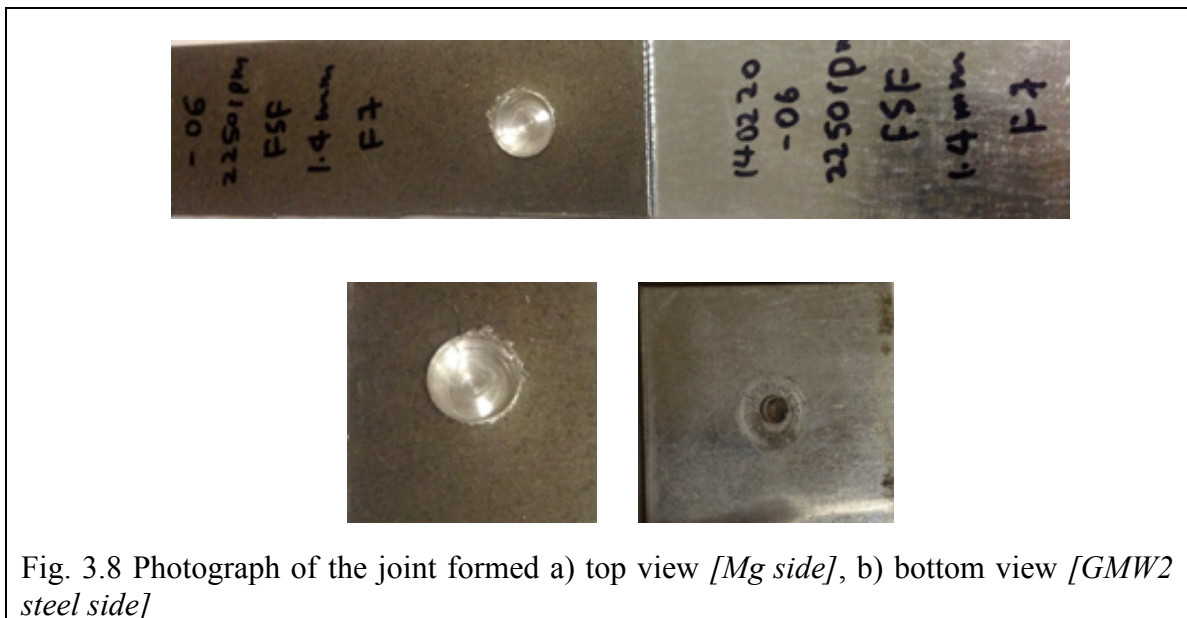


Fig. 3.7 Basic machining setup for Mg/Steel combinations

The plunge depth for this trial was 1.9mm, 2.0mm and 2.1mm. The feed rate was fixed at 5mm/min, the spindle speed is maintained at 3000rpm for this sets of testing samples. As shown in the figure above, the strength of the joint is approximately 3000-4000 N. The axial force and torque from the dynamometer is about 4kN for this sets of samples.

The magnisium is extruded through the prefabricated hole in the steel coupon. This makes the pin or the neck and the head which ensure the mechanical interlocking. Without the head, the samples will be easily separated since the neck would not be able to secure the aluminum to the steel on its own. The appropriate dimensions for the head of the formed joint are 3mm for the diameter and 0.6mm for the height, which is conformed to the single hole anvil geometry.



The tensile shear testing showed that the failure mode of this joint is bonding delamination where the brazed joint broke down. The pulling force of the machine is

increasing until the moment it reaches the critical value. The failure happened at the speed of sound. [Slandjan, 2013]



Fig. 3.8 Broken samples' result from the PIN failure. From left to right: upper plate viewed from the bottom, bottom plate viewed from the top

Majority of this type of joint were failed at the extruded pin, since the majority of the material formed for the pin is Mg, this will be the weakest point of the joint. By comparing the joint made by the Mg/Steel and Al/Steel, the shape of the Mg/steel formed joint is orderly, however, since the Mg was deformed and the interlock is made by the deformed Mg, the joint is not strong compare to the Al/steel joint.

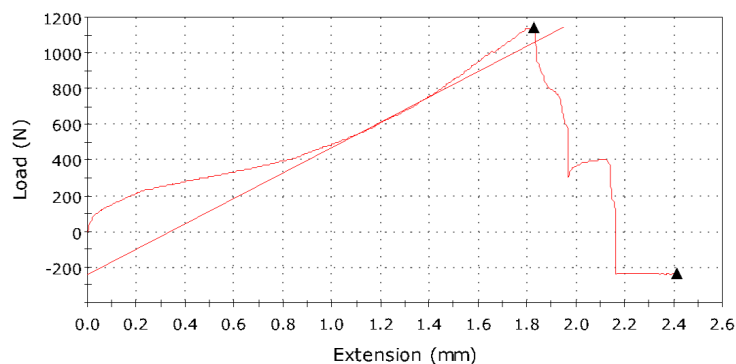


Fig. 3.9 Lap shear strength testing output of Mg/steel traditional FSF single pin setup

The strength for the joint formed by Mg/Steel combination is 1000-1200 N from the average results of 6 samples. Which indicates that the joint could support 1000-1200 N of force before it breaks down.

The area under the curve shows that the joint will fail rapidly when it reaches the critical point. This joint can absorb less energy before rupturing, which is one of the limitations of this joint.

### 3.2.2. Mg/GMW2 with clinching

This part of the experiment is done to test the strength of the joint formed when the Magnesium coupon on the top and GMW2 steel on the bottom. However, instead of using the single hole anvil the new raised pin anvil was used. The purpose of this was to form a clinching joint with friction force, and then compare the strength between this and the normal setup. Eventually, the different setups were established for FSF process.

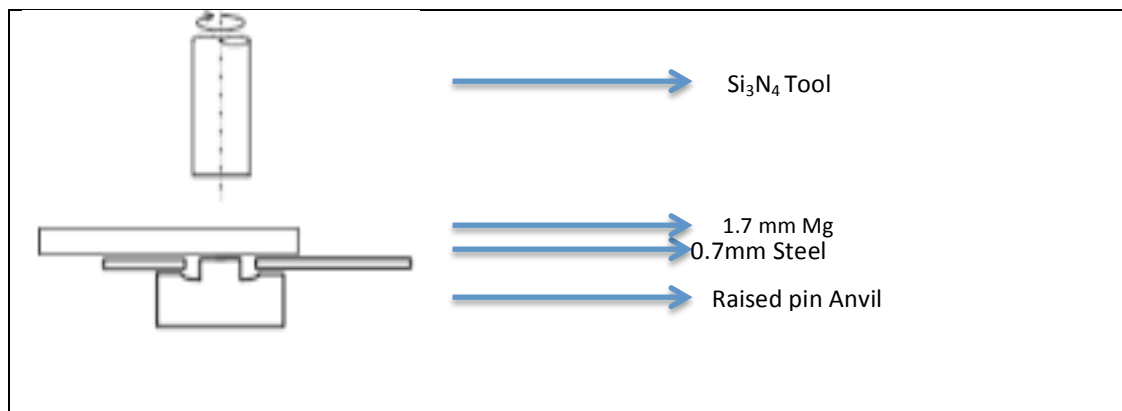


Fig. 3.10 Basic machining setup for Mg/Steel combinations with clinching anvil

The plunge depth for this trial was 1.9 mm, 2.0 mm, 2.1 mm and the feed rate was fixed at 5mm/min, the spindle speed is maintained at 3000rpm for these sets of testing samples. Two sets of experiment were done with different machining setup. As shown in the figure above, the strength of the joint is approximately 3000-4000 N. The maximum axial force and torque from the dynamometer is about 6kN for this sets of samples.

An interlock similar to clinching joint was formed after the machining, where the deformed magnesium flowed into the anvil and formed an interlock. It is observed that during the machining only the magnesium was softened and deformed. The bottom steel sheet was pushed, but without any deformation. After machining, a similar clinching ring formed by the top sheet material Magnesium, which is the main interlock for this joint. The figure below shows the joint formed. However in order to form this joint, it often suffers from high tool wear, which raises production costs.

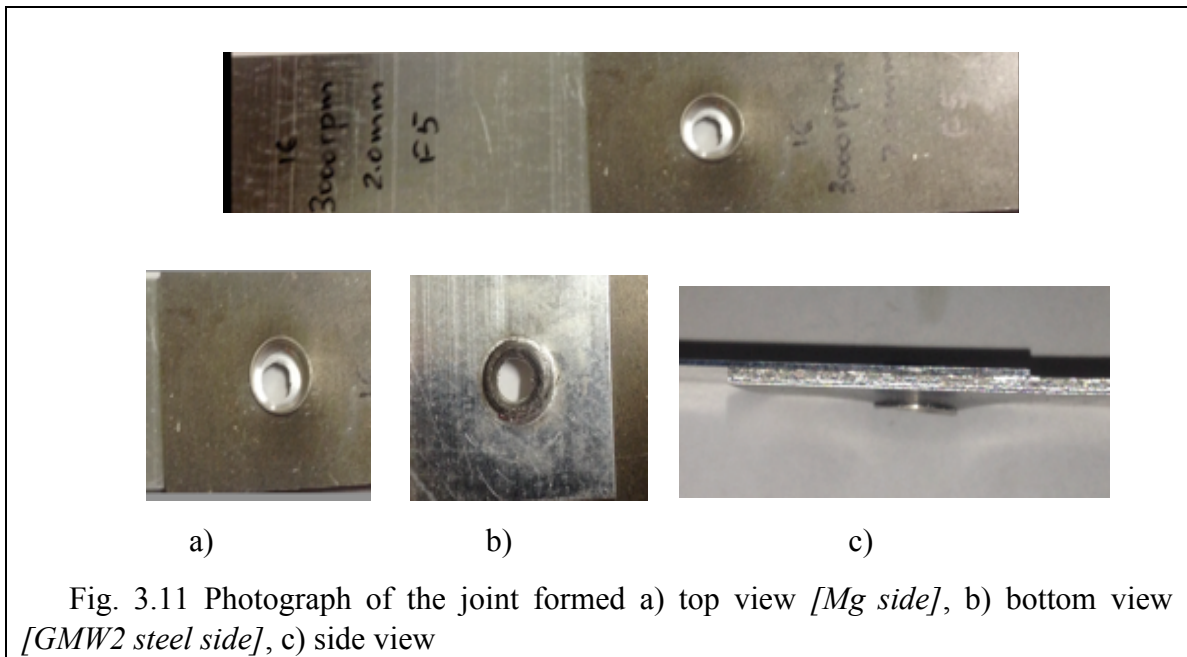


Fig. 3.11 Photograph of the joint formed a) top view [Mg side], b) bottom view [GMW2 steel side], c) side view

The appropriate dimensions for the clinching rings of the formed joint are 12.90mm for the outer diameter and 8.00mm for the inner diameter. The average height of the clinching ring was about 1.30mm.

A tensile shear testing was implemented after the joint formed. The failure mode of this joint is neck shear. In this case, the specimens pulled on the lap-shear strength machine would fail in their weakest point, the neck. [Slandjan, 2013]

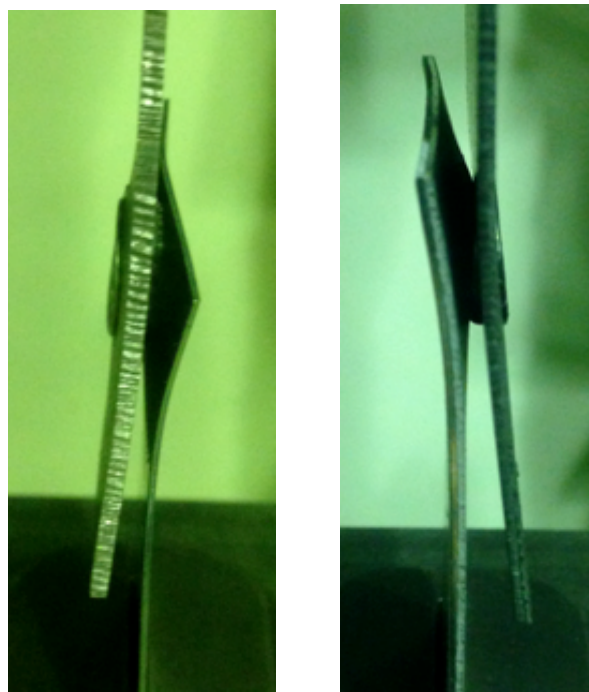
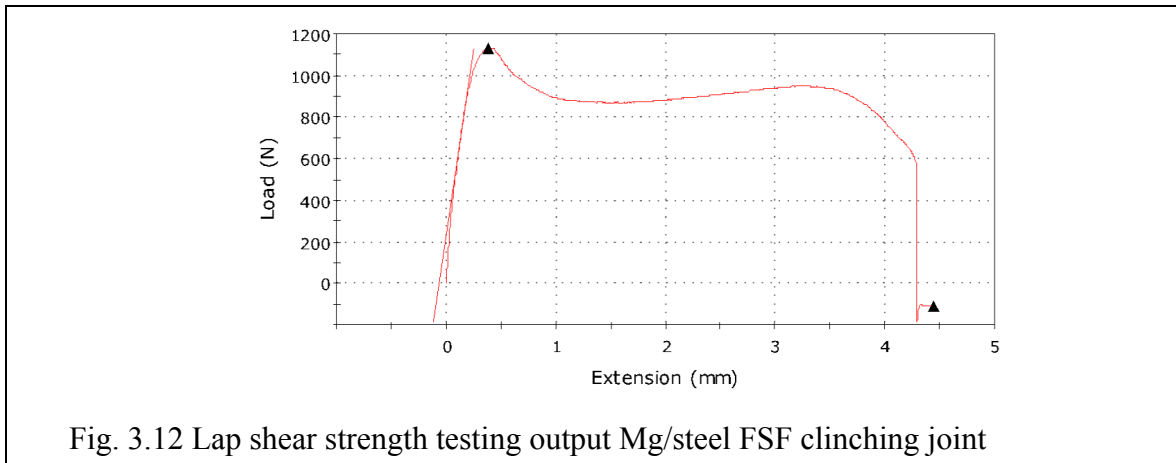


Fig. 3.13 Breaking process during the lap shear strength test.

As shown above, the joint start to fail when the steel coupon started to bend. Once a gap formed in between of the two coupons, the stress strain curve start to drop. It will stay there for a while before the joint is completely ruptured. For Mg/Steel joint, the steel start to bend first, and then the clinch joint formed by magnesium coupon is being ruptured.



The strength for the joint formed by Mg/Steel modified clinching is 1200-1300 N from the results of 8 samples. By using the same parameters, the average strength of the Al/Steel combination was 2000N.

The stress strain curve showed that the joint could stand for another 4mm extension after it reaches the ultimate tensile strength. Which means this is a tougher joint; even the joint starts to fail it still can hold a large amount of strength until it completely fell apart. This experiment results is attained from the area under the strength curve. The larger the area is, the better the joint would be.

### ***3.2.3. 1010-1018 steel /Mg***

The testing of the joint formed by the magnesium and steel with magnesium on the top was tested. However, it is proved that the strength of the joint formed by the steel and

Al combination with steel on the top has a better joint strength. It would be interesting to compare the strength of Mg/steel and steel/Mg. In this section the 1.5mm 1010-1018 steel was placed on top of the 1.7mm Magnesium with a diameter of 5mm predrilled hole. The strength and also the toughness of the joint were tested after the joint formed.

For this experiment, the same experimental setup as the steel/Al, and the figure below shows the schematic of the basic machining setup.

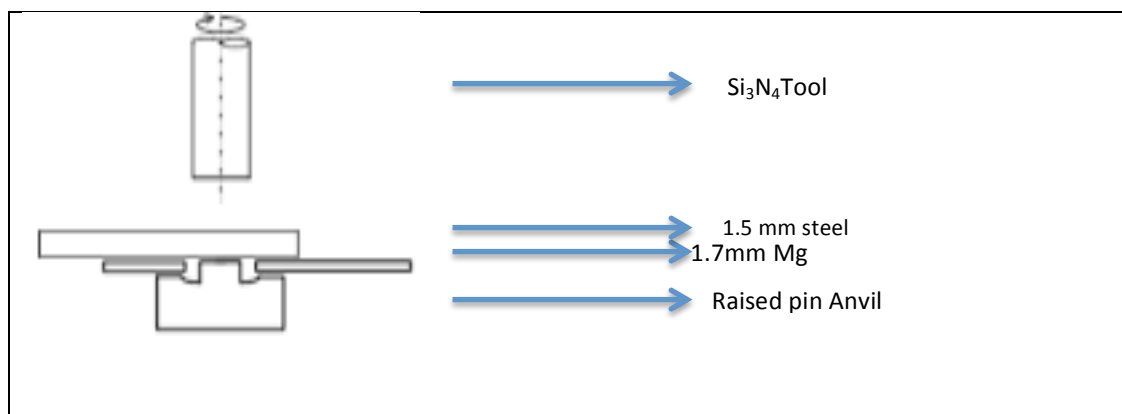
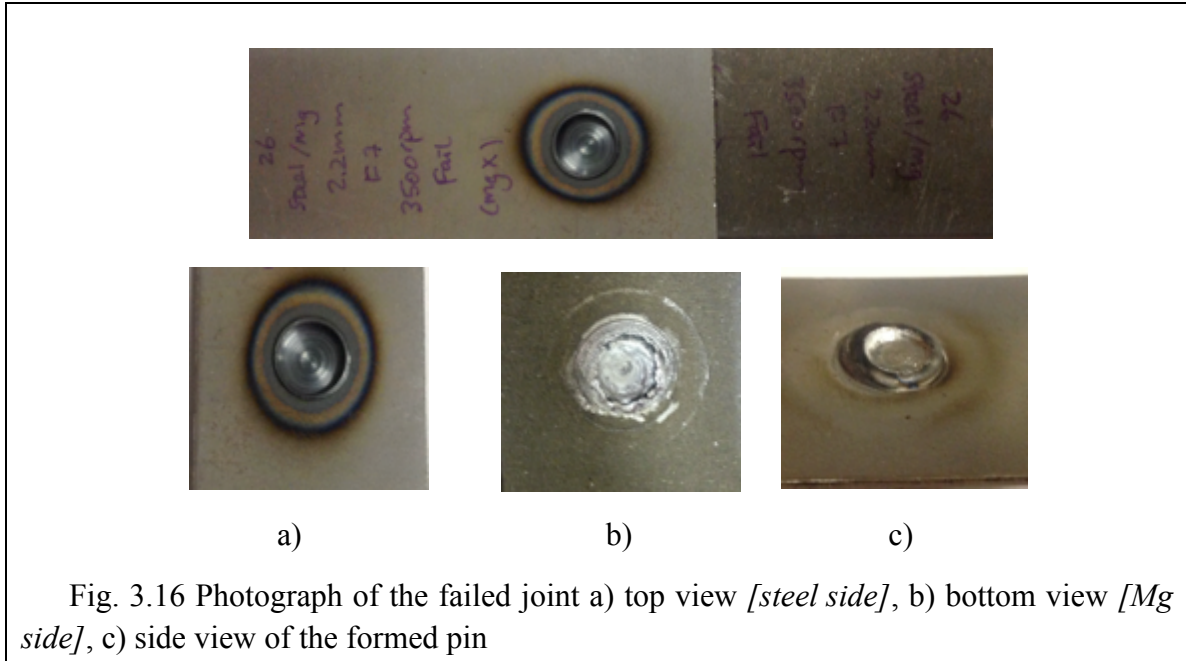


Fig. 3.15 Basic machining setup for Steel/Mg combinations

The plunge depth for this trial was 2.0mm, 2.2mm, and the feed rate was 7mm/min, the spindle speed is maintained at 3500rpm for this sets of testing samples. As shown in the figure above, the strength of the joint is approximately 3000-4000 N. The axial force and torque from the dynamometer is about 6kN for this sets of samples.

An interlock similar to clinching joint was formed after the machining, where the deformed steel flowed into the anvil and formed an interlock. It is observed that during the machining only the steel was softened and deformed. Magnesium behaves the same as aluminum coupons, it was deformed, which means the deformed steel destroyed the bottom Mg.



The appropriate dimensions for the clinching rings of the formed joint are 12.0 mm for the outer diameter and 8.0 mm for the inner diameter. The average height of the clinching ring was about 0.6mm

From the pin formed by low carbon steel, we could predict that the clinching similar friction formed joint was made by the steel or the material on the top. However, the high temperature softened steel destroyed the bottom magnesium. As shown in figure 3.16 c), instead of the formed pin bent around the bottom plate, the pin formed by the steel went vertical to the bottom plate. The mechanical joint was not formed at all for all the trials.

### 3.3 Carbon fiber composite and Al combinations

#### 3.3.1. Carbon fiber nylon composite and Al combinations

The setup for carbon fiber nylon composite and Aluminium combination was different from the other setups, the reason for this is that the melting temperature for 3.0 mm carbon fiber composite is much more lower than 1.0mm aluminium. The CFRP with

nylon matrix will be softened first after friction stirring, it would penetrate into the eight pre-drilled ring holes on the top aluminium coupon.

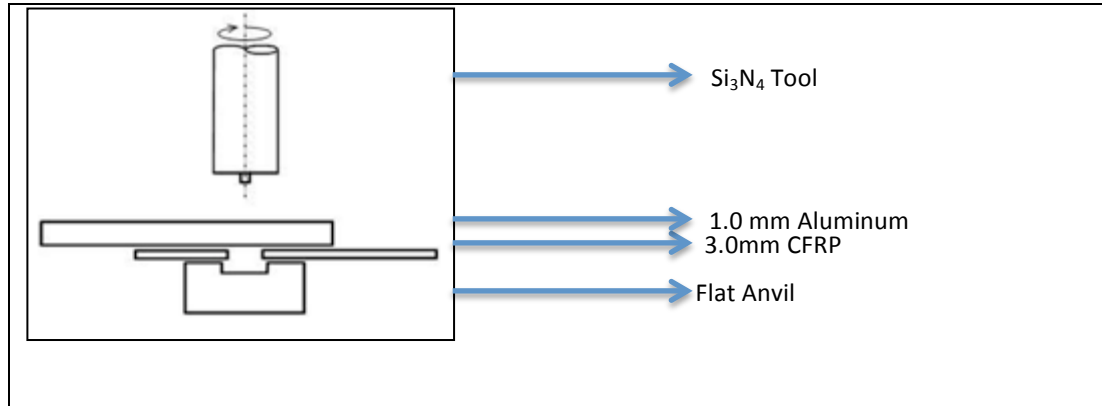


Fig. 3.17 Basic machining setup for Al/CFRP combinations

For this experiment, 5 different plunge depths were tested to find the optimum plunge depth, and also 3 different feed rates were used. The optimum plunge depth for this trial was 1.9mm and the feed rate was 10mm/min. The spindle speed is maintained at 3000rpm for these sets of testing samples. As shown in the figure above, the strength of the joint is approximately 3000-4000 N. The axial force from the dynamometer is about 6kN for these sets of samples.

The joint formed is shown in the photo below, all the predrilled ring holes were filled with the softened composite material. However, the material of the joint formed is extremely brittle, it is easily broke off. It is predicted that the major part of the joint would be the center of the joint, where the aluminum is pushed into the carbon fiber, and form a joint in the center.



Fig. 3.18 Photograph of different joint formed

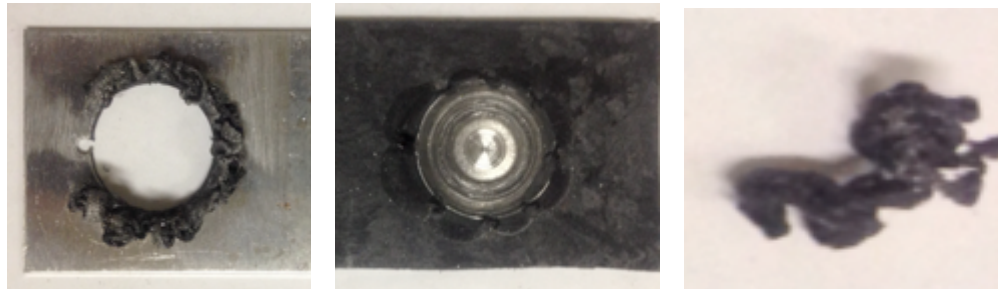


Fig. 3.19 Broken samples' results from the neck shear failure. From left to right: upper plate viewed from the top, bottom plate viewed from the top, chips off from the joint.

As shown in the figure above, most of the samples formed by Al/CFRP combination were failed at the neck of the joint, which is the weakest point of the joint.

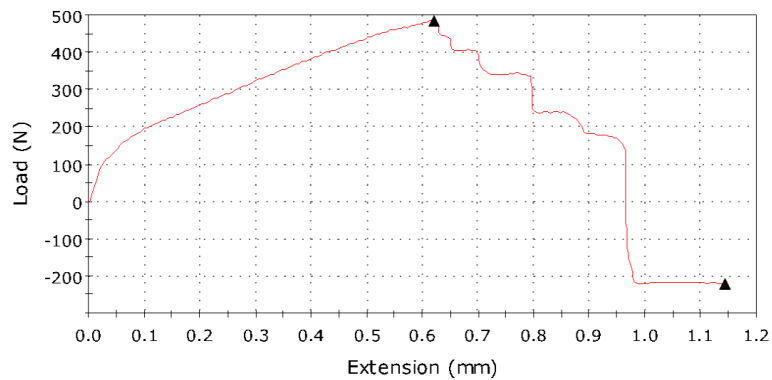


Fig. 3.20 Lap shear strength testing output for joint made by Al/CFRP

The strength for the joint formed by Al/CFRP combination with the optimum plunge depth and appropriate ring hole diameter is 1300 N from the average results of 16 samples.

The load extension curve is similar to the traditional FSF multi-pin samples. When the joints start to break, the opposite formed joint start to peel off one by one, so that the stress strain curve shows the different steps of sample breaking.

### *3.3.2 Carbon fiber reinforced polymer and Al combinations*

There are two types of carbon fiber used for this experiment, they are different with different thermoset. One with epoxy composite another with nylon matrix. However, it was hard to form a joint with the CFRP with epoxy, since the CFRP with epoxy is hard to be softened. Another reason for this is that the material placed on the top was hard to flow into the predrilled hole on the CFRP, because it will be stoped by the damaged thermoset.

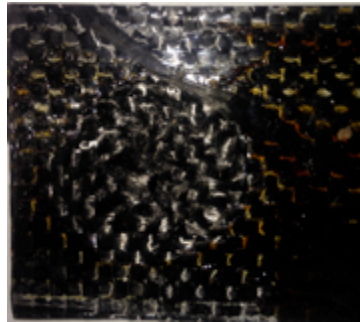


Fig. 3.21, Damaged CFRP (Epoxy)

The predrilled hole on the CFRP (Epoxy) was covered by the reinforcement carbon fiber.

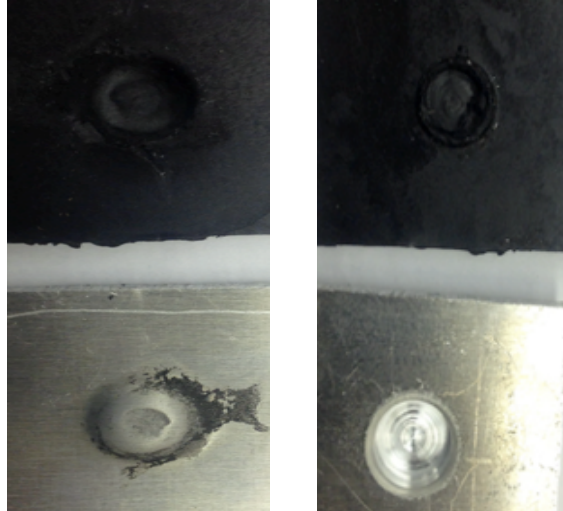


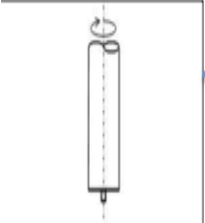
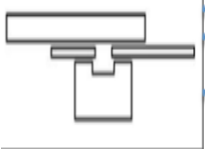
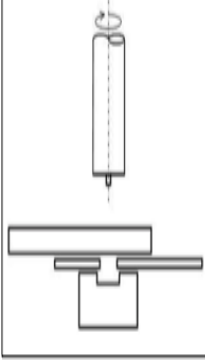
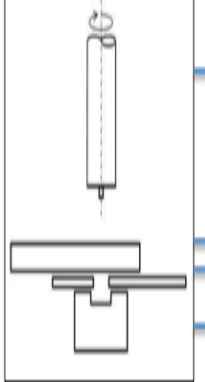
Fig. 3.22 Damaged CFRP (Nylon)

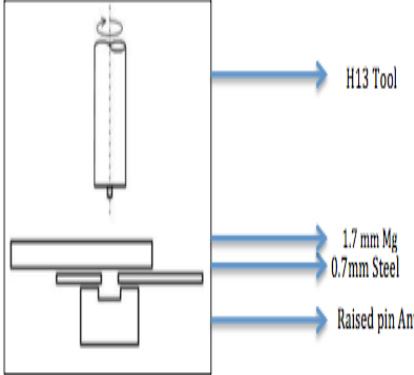
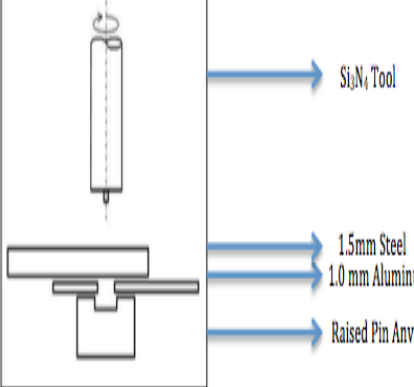
The predrilled hole on the CFRP (Nylon) was damaged by the machine, where stops the Al penetrate into the hole to form a joint.

### 3.4 Summary of the results

These five different material combinations are done with the same CNC machining and also the same fixture. We could conclude that the possibility of forming a joint with different light material combinations. The table below is a results' summary of all the different material combinations, where the possibility of the formation of the joint, the strength of the joint, and the toughness of the joint are shown.

**Table 3.1 Table summaries of the results**

Materials	Experiment setup	Possibility (Pass/Fail)	Strength	Toughness
Al/CFRP (Epoxy)	 <p>Si<sub>3</sub>N<sub>4</sub> Tool</p>	Fail	--	--
Al/CFRP (Nylon)	 <p>1.0 mm Aluminum 3.0 mm CFRP Flat Anvil</p>	Pass	1000-1300N	Tough
Steel/Mg	 <p>Si<sub>3</sub>N<sub>4</sub> Tool 1.5 mm steel 1.7 mm Mg Raised pin Anvil</p>	Fail	--	--
Mg/Steel	 <p>H13 Tool 1.7 mm Mg 0.7 mm Steel 3mm Single hole Anvil</p>	Pass	1100-1300N	Brittle

<p>Mg/ GMW2Steel</p>		<p>Pass</p>	<p>1300-1400N</p>	<p>Tough</p>
<p>Steel/Al</p>		<p>Pass</p>	<p>3500-4000N</p>	<p>Tough</p>

## Chapter 4 Metallurgy

Metallography is able to provide information on phases and their distribution, and material deformation. Two FSF clinching joints were viewed under SEM, joints made by the Low carbon steel/Al, and Mg/GMW2 steel. The reason for doing SEM is to test whether the diffusion happens during the machining process and to find the FSF clinching joint composition.

### 4.1 Sample Preparation

The cross section of the sample prepared by a diamond saw and cutting fluid. Cutting is done in a way to ensure that the sample is not subjected to heat treatment. The sample was then mounted in epoxy resin. The next step is to carefully polished samples. First rough polishing is done with silicon carbide paper and then polished with fine alumina various sizes suspension. The final polishing was performed using 0.5-micron diamond suspension. Once this is done, the sample was washed, and dried with compressed air, to ensure that no corrosion occurs. And then stored in a desiccator until further analysis.

Before SEM, the sample needs to be coated with carbon coating using sputter coater, and also a layer of copper needs to be stick on the epoxy to ensure the prepared sample surface conductive.

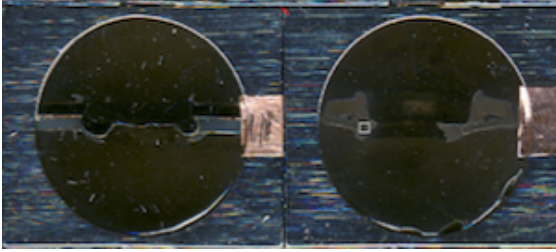


Fig. 4.1 Prepared samples for SEM

## 4.2 SEM

Instead of using light, Scanning electron microscope (SEM) uses electron to form an image. The SEM has much higher resolution, so closely spaced specimens can be magnified at much higher levels, because compare to lenses the SEM uses electromagnets to control the degree of magnification. These advantages allow SEM to provide a clearer image than microscopy. A beam of electrons is produced at the top of the microscope by an electron gun. The electron beam follows a vertical path through the microscope, which is held within a vacuum. The beam travels through electromagnetic fields and lenses, which focus the beam down toward the sample. Once the beam hits the sample, electrons and X-rays are ejected from the sample. Detectors collect these X-rays, backscattered electrons, and secondary electrons and convert them into a signal that is sent to a screen similar to a television screen. This produces the final image.

EDX rapid qualitative and quantitative analysis of elements is used to provide the sample of 1 to 2 microns shallow depth. First, the region of interest is selected, and then detects the different phases of the selected area. Depth is important because the surface area below is unknown.

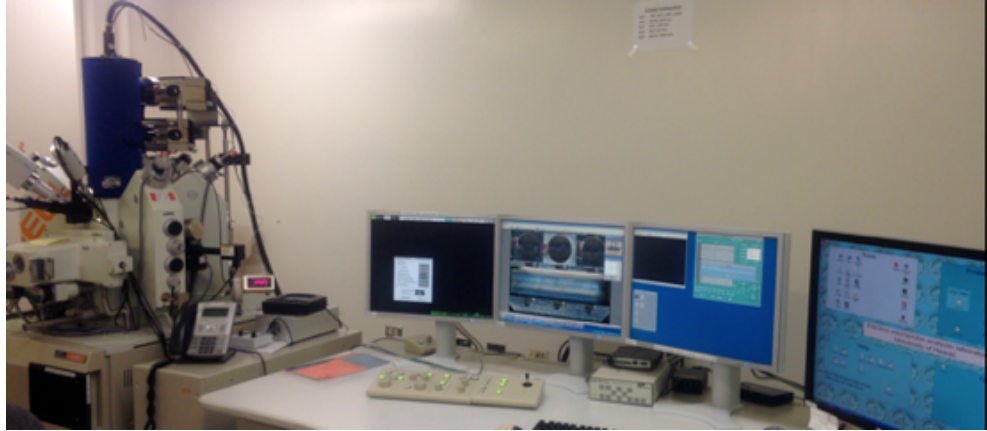


Fig. 4.2 Basic setup of SEM

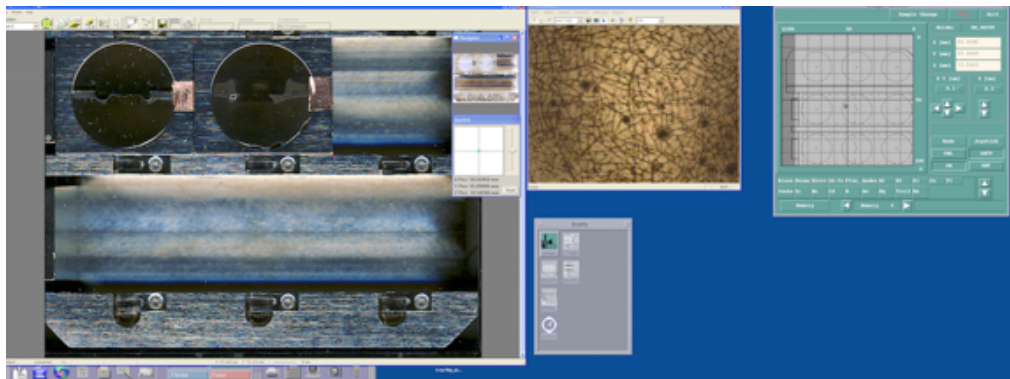


Fig. 4.3 Monitor output from SEM

The figure above shows the first two monitor's output of the results, where the left screen shows the navigation of the electron beam, and the window on the right shows the surface output of the sample, which is used to prevent the bubbles in the epoxy being exploded.

### 4.3 SEM results

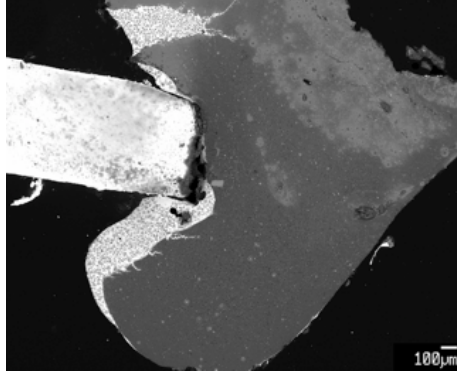


Fig. 4.4 Mg/GMW2 steel clinching

Figure above shows the right corner of the clinch joint, where the darker material is Mg and the lighter material is steel. As shown in the figure above, pushing Mg down to curve around the bottom steel coupon formed a clinch joint. This is an interlock from the joint, where it is the major part of the joint.

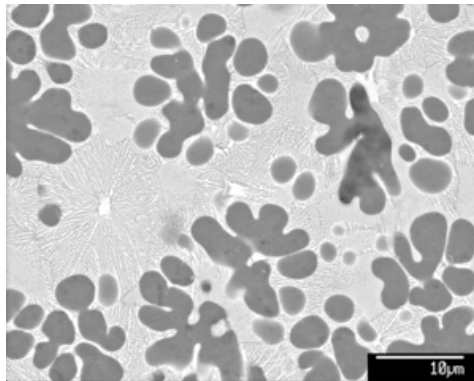


Fig. 4.5 Two phase- Mg and Zinc

As shown in the figure 4.5 above, there are some material mixture zones at the two material interfaces. We zoomed in to find the material composition of this mixture. The detailed material composition of this area is tested and shown in the figure below. There is a brazed layer formed by the coating of the steel and also the Mg, which happens to the Al/steel traditional single pin joint too. As mentioned in the previous research, diffusion can occur in two different mechanisms: vacancy and interstitial. Here, the primary

mechanism is the vacancy type of diffusion where a host (magnesium) or substitution atom (zinc) exchanges places with a vacancy. The main mechanism definitely cannot be the interstitial diffusion method where an interstitial atom jumps into an adjacent unoccupied interstitial site since the two atoms are close in radius. In addition, it is obvious that interdiffusion (impurity diffusion) plays a role, and that can be seen especially with oxygen, which comes from the atmosphere during the FSF process and is unavoidable. [Sladjan, 2012]

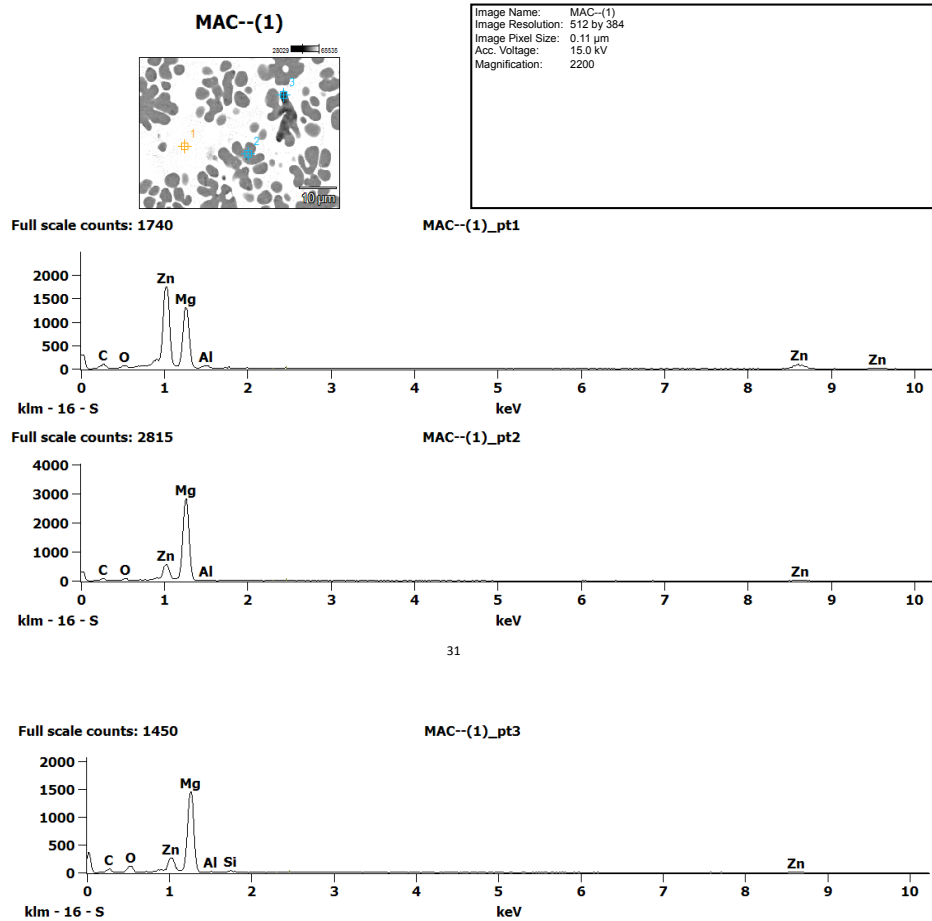


Fig 4.6 Output of material composition for the formed two-phase mixture

The figure below shows the interlock formed by the FSF clinching process, the Mg penetrates under the steel and formed an interlock. This is the major component of the mechanical interlock. However, as shown in the figure, there is a thin layer of Mg on top of steel, this is always the weakest point of the joint. From the lap shear tension test, the majority of the joint failed at this point. In order to solve this problem, it is better to use a thicker Mg coupon, and also change the plunge depth to a smaller number.

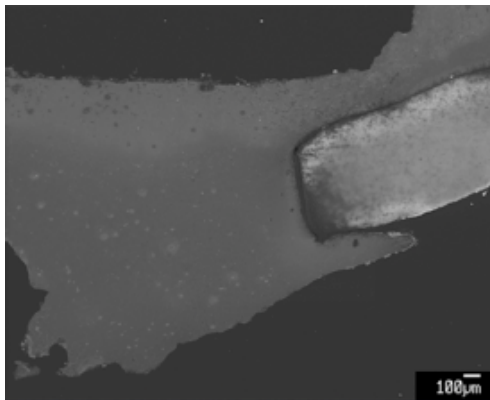


Fig. 4.7 Close view of the clinch joint on the other side

As shown in the figure above, the friction force does not affect majority of the interface, and not too much intermetallic structure formed at the clinch joint.

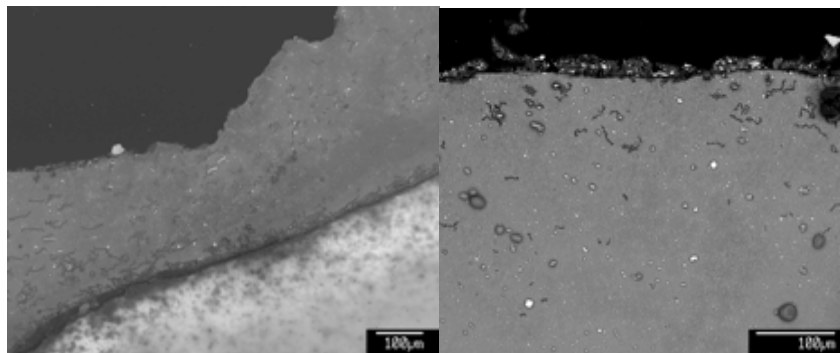


Figure 4.8 Close view at the interface

Figure above is a close view of the interface; where there is no diffusion occurred. This ensures the strength of the joint, there is no intermetallic material formed at the interface.

In conclusion, the SEM results of the Mg/steel combination shows that, the joint formed is a mechanical joint, and there is a little diffusion occurs at the clinch area. Majority of the interface does not have diffusion.

Figures below are obtained from the steel/Al material combination; it is expected to form a similar joint as the Mg/steel.

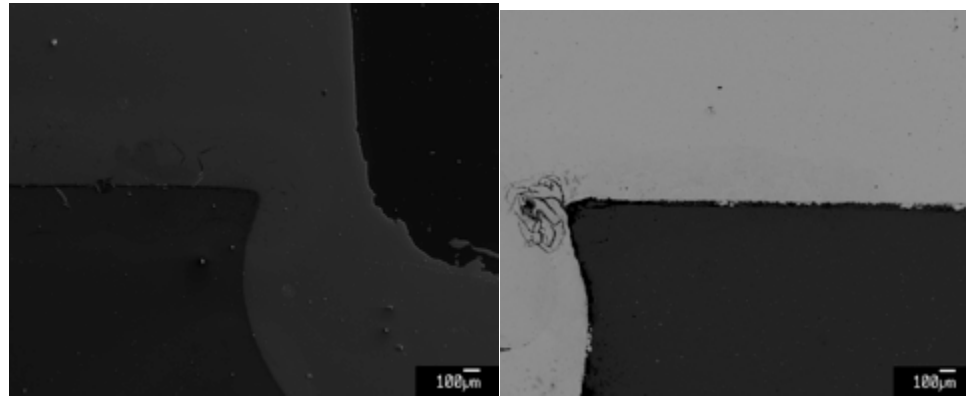


Fig. 4.9 Steel/Al clinching formed interlock. Left: SEI view. Right: Comp view

This is an image captured at the upper right part of the two material interfaces, it is observed that, there is a hook formed at the interface, and also a little bit material mixture at the tip of the hook. This is one of the major component of this joint. As shown above, the aluminum coupon was covered with pushed down steel material. Not too much diffusion occurs here, which proves that this is a mechanical joint. However, this is the weakest point of the joint, where there is a thin layer of steel at the tip hook. It is better to make the diameter of the predrilled hole on the aluminum coupon bigger.

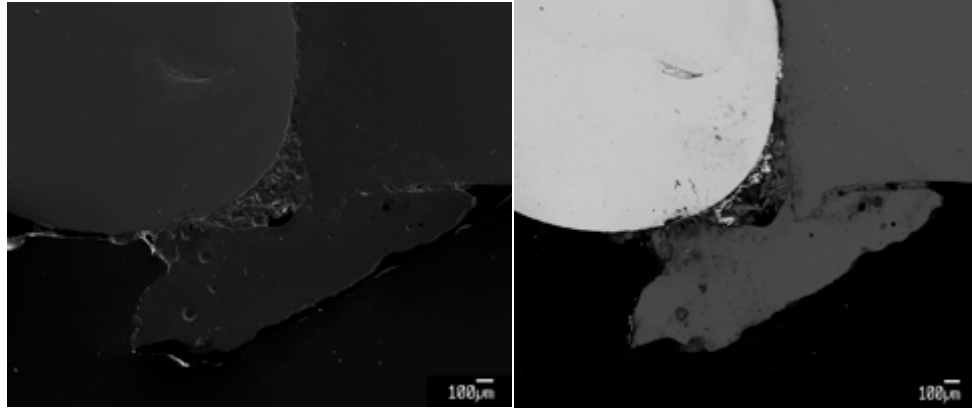


Fig. 4.10 Damaged Al at the bottom, right: SEI view, left: comp view

It is expected to form a similar joint at the bottom of the joint, where the steel curved around the aluminum coupon. However, from the SEM results, the aluminum is pushed and destroyed by the harder steel. This actually did not affect the quality of the formed joint, since there is already an interlock formed on the top interface.

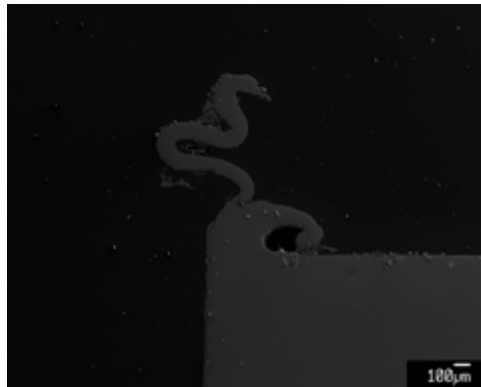


Fig. 4.11 Formed chips on the top right

It is observed that there are similar chips formed for all the friction samples; the material is squeezed at the place next to the tool.

## Chapter 5 Conclusion

### 5.1 Summary

In this research, the possibility of forming a joint by different material combinations was tested. This research helped to identify the suitable materials ranges for FSF process, as well as determine the optimum machining setup for different material combinations. The joint formed by the harder material flowing into the anvil cavity was stronger than joint formed with softer material. For both machining setup, the bottom coupon needs to be thinner than the top coupon to prevent damage. For clinching machining setup, top coupon needs to be thick enough to provide enough material to form an interlock. Harder material could be placed on the top with FSF clinching setup. Not too many material diffusion at the interface of the joint formed by the FSF clinching.

### 5.2 Conclusions and Contributions

#### *5.2.1. Joint formed by aluminum and steel:*

- Two types of steel had been used for the experiment. The stiffness of GMW2 steel makes it difficult to be softened to form a mechanical joint, and also the material from 0.7mm thick steel was not enough to form a mechanical clinching joint. So that *GMW2 steel could only be used as the bottom plate.*
- 1.5mm low carbon steel was softened enough to form a clinching joint, which was one of the strongest joint formed. Since the joint was formed with steel instead of aluminum. *Joint formed with harder material is stronger.*

- The edge of predrilled hole on the bottom coupon was affected; a small amount of diffusion occurs here. However, *majority of the formed clinching joint material was from steel.*
- A thicker coupon on the top could supply enough material to form a joint with enough material. *Raised pin anvil could only be used with a thicker coupon on the top.*
- The plunge depth should be more than the thickness of the top coupon to make sure there is enough material to form a clinching joint. *Clinching joint requires more material than traditional single pin FSF joint.*
- The joint strength has an average of 4k-5kN. The average of the area under the stress strain curve was large. *This is a strong and tough joint, which is applicable for automotive industry.*
- Majority of the joint were failed at the curved interface, where the formation of big heights and widths of the curved interfaces resulted in the high tensile shear force of the friction stir formed clinching joint.

### ***5.2.2 Joint formed by Magnesium and steel:***

- By applying GMW2 steel as the bottom coupon, the softened magnesium flowed into the anvil to form a mechanical joint. The GMW2 steel was not impressed, not even the zinc coating. *This is a mechanical joint without affecting the bottom coupon.*
- The magnesium formed a clinching joint, where more material flowed to form a joint compare to the joint formed by steel, because magnesium is softer than steel.

- The magnesium formed the traditional single pin FSF joint, however there is no fusion joint formed between these two plates. The area under the tool was not affected. Compare to Al/Steel single pin FSF joint, this is a weaker joint.
- From the joint, we could see that the friction force did not affect the bottom of the magnesium. *The punching force played a role on making the mechanical joint.*
- Majority of the traditional single pin FSF joint were failed at the neck of the pin, since this is the weakest point of the joint. However, for the clinching joint, the majority of the joint failed at the notches, which create a higher strength joint.
- Since the less material were used to form the traditional single pin joint than the clinching joint. *Joint formed with the raised pin anvil is stronger.*

### 5.2.3 Joint formed with CFRP:

- Two types of CFRP were used to test the possibility of forming a joint. CFRP (Epoxy), and CFRP (Nylon matrix).
- For Al/ CFRP, both CFRP will be destroyed or melted during friction stirring. The predrilled hole on CFRP filled with epoxy or melted nylon matrix which blocks the top material penetrate through. *No joint formed with CFRP on the bottom for both traditional single pin FSF process and clinching FSF process.*
- To prevent both CFRP from destroying, a washer was applied in between of the two coupons. However, the washer was pushed away during the process. *To prevent the mesh being destroyed, a larger and thin washer needs to be stick onto the bottom CFRP.*
- Joint formed from Al with eight ring holes/ CFRP (Nylon matrix), had an average strength of 800N, standard deviation was 800N.

- The joint filled and formed in the eight rig holes broke one by one during lap shear tension test. *This experimental setup increases the toughness of the joint.*
- This experimental setup is suitable for material with lower melting temperature on the bottom.
- The material filled in the eight ring holes is brittle.

In conclusion, joint formed by clinching has an industry potential. Joint formed with harder material has a larger strength. For the traditional single pin FSF process of Mg/GMW2 steel, no thermal and mechanical effects occur on the bottom of the weld and in between the sheets by the downward moving stirring tool. This is different from the Al/steel observations. The reason for this is the Magnesium was thicker than the Aluminum and also the melting temperature of magnesium is lower than aluminum, where we could predict that the highest temperature reaching for Mg/Steel is lower than Al/Steel combination.

During the tensile shear tests, the cracks in the joint initiates at the notches of two sheets and grew along the curved interfaces between the two deformed sheets. This is because the strength of the curved interface was smaller than that of the sheet materials. As a results, the formation of big heights and widths of the curved interfaces resulted in the high tensile shear force of the friction stir formed clinching joint.

### **5.3 Contributions to the Literature**

The following specific contributions were made in this research:

1. Aluminum, steel, magnesium could all be formed to create a joint with dissimilar second material by FSF.

2. Steel can be formed in a clinching geometry with a secondary material with inferior mechanical and thermal properties.
3. Not too much diffusion happens at the interface of the two coupons, which prove that this is a mechanical joint.

## 5.4 Future research

In this research the possibility of joint forming by different material has been addressed. In addition, the new FSF clinching joint microstructure was studied to prove the forming of the mechanical interlocking. With the current result, it is suggested that more experimental data is needed to better understand the FSF clinching process. Different thickness coupons could be tried with the raised in anvil, to find the best thickness of the material used for this type of joint. For this experiment we only could prove that the GMW2 steel could not place on top. And also the top coupon needs to be thick enough to provide enough material for the clinching joint.

During this experiment, it is proved that the plunge depth is one of the important parameters to form the joint. Different thickness of the material and also different plunge depth should be tried to find the optimum ratio of this two significant factors.

By comparing the joint strength of the traditional single pin joint and the new clinching joint, the traditional single pin joint was stronger, since it had more contact surface than the clinching joint. Different tool geometry need to be tried for the clinching joint, it is predicted that by varying the shape of the tool, the area of the formed joint will be increased, where the strength of the joint could be increased too.

For the clinching joint, the diameter of the hole on the bottom plates, anvil cavity diameter, to tool diameter ratio need to be determined with more experimental trial and error approaches.

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