FEASIBILITY OF FORMING Al5052-POLYMER HYBRID CLINCH JOINT WITH ROUND GROOVED CLINCH SET

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**A project report submitted in partial fulfilment of the
requirements for the award of Bachelor of Engineering
(Honours) Mechanical Engineering**

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DECLARATION

I hereby declare that this project report is based on my original work except for citations and quotations which have been duly acknowledged. I also declare that it has not been previously and concurrently submitted for any other degree or award at UTAR or other institutions.

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APPROVAL FOR SUBMISSION

I certify that this project report entitled **FEASIBILITY OF FORMING Al5052-POLYMER HYBRID CLINCH JOINT WITH ROUND GROOVED CLINCH SET** was prepared by **Tan Yi Ying** has met the required standard for submission in partial fulfilment of the requirements for the award of Bachelor of Engineering (Honours) Mechanical Engineering at Universiti Tunku Abdul Rahman.

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ABSTRACT

Joining process is the key enabler of light weight and multi-material design. Due to the different natures and properties of each material, joining of dissimilar materials is relatively challenging as compared to joining of similar materials.

Among many of the joining methods available in the industry, mechanical clinching represents a viable solution in addressing the difficulty faced in joining dissimilar materials. It is a process which join material sheets together by plastically deform them and create an interlock between them. It is a fast, simple and environmental-friendly process which does not introduce any extra element to the assembly. To date, there are numbers of researches have been conducted to study the suitability of joining metal with polymer by using mechanical clinching process. One of the studies reported that round grooved clinch dies are not feasible for joining aluminium and polymer. Thus, in the presence study, the feasibility of joining Aluminium 5052 with polymers by using round grooved clinch die was investigated.

It was found that round grooved clinch die is able to produce sound clinched connection between Aluminium 5052 and polymers such as polycarbonate, polyvinyl chloride and high impact polystyrene with the maximum shear strength of 1.28kN, 1.21kN and 0.8kN respectively. It was also found that punch load has great impact on the joinability and failure modes of the hybrid structure.

Besides, numerical simulation was also conducted in the study and the results obtained were in agreement with experiment data and shown a strong experimental - numerical correlation. This proves that the approaches used in the finite element analysis is valid and it is suitable to be used to optimize joint strength and predict failure in the future work.

This study has proven the feasibility of joining metal with polymer by using round grooved clinch die and this finding is significant in terms of it may have huge impact on introducing industry a simple, fast and eco-friendly joining method to join dissimilar material.

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$\bar{\sigma}_Y$	Average flow stress, Pa
t_U	Length of the undercut, m
μ	Friction coefficient
$\bar{\sigma}_f$	Fracture stress of upper sheet, Pa
A_N	Projection area of the neck, m^2
R_P	Clinching Punch radius, m
t_N	Neck thickness, m
σ_{true}	True stress, Pa
$\sigma_{engineering}$	Engineering Stress, Pa
$\varepsilon_{engineering}$	Engineering strain, mm/mm
ε_{true}	True strain, mm/mm
$\varepsilon_{\ln}^{plastic}$	Logarithmic plastic strain, mm/mm
E	Young’s modulus, Pa

GHG	Green House Gas
PC	polycarbonate
PMMA	polymethyl methacrylate
PS	polystyrene
GFRP	glass fibre reinforced polymer
CFRP	carbon fibre reinforced polymer
FEA	Finite Element Analysis
3D	Three Dimensional

CHAPTER 1

INTRODUCTION

1.1 General Introduction

The awareness of sustainability for both environment and resources among society have greatly impacted the automotive industry nowadays. For instance, before the oil crisis in 1973, car was used to be heavy, fuel consuming and low efficiency. However, as the petrol price increased tremendously due to the shortage of petrol, society started to be aware of the scarcity of the resources. Thus, car manufacturer started to downsize their product, apply lightweight design and use smaller engine on their product to reduce fuel consumption.

Besides, transportation sector, including all modes of transport which carry peoples or goods is one of the main contributors of greenhouse gas (GHG) emission globally. As depicted in Figure 1.1 , it can be seen that transportation contributed 14% of greenhouse gas emission in 2010 (Intergovernmental Panel on Climate Change, 2014). Thus, Emission standard was implemented globally to limit the permissible amount of GHG emission being released into atmosphere by on-road and non-road vehicle. Consequently, car manufacturers have to ensure their product meet the emission standard, while catering customers' needs in performance and aesthetic aspects.

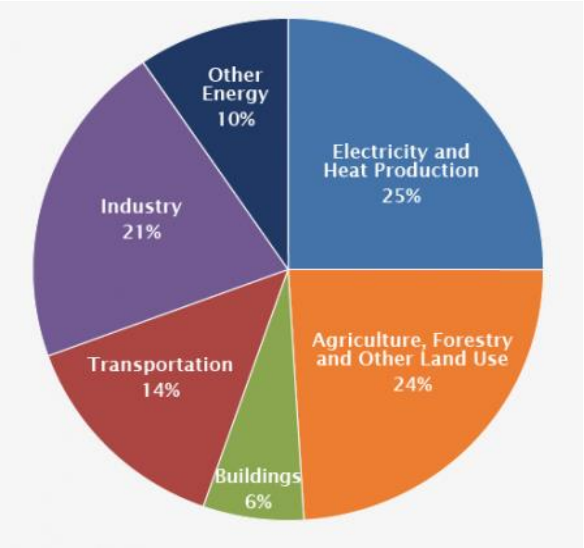


Figure 1.1 Greenhouse gas emission by sector (Intergovernmental Panel on Climate Change, 2014)

One of the measures has been taken by designers to tackle the problem is by acquiring lightweight design concept on vehicle to reduce the fuel consumption of vehicle which in turn reduce GHG emission. This is due to the fact that fuel consumption is directly influenced by the weight of the vehicle (Del Pero, Delogu and Pierini, 2017). Figure 1.2 shows the impact of material substitution on mass of vehicle and GHG emission. As the weight reduces, the power required will be reduced, and consequently the fuel consumption will be reduced.

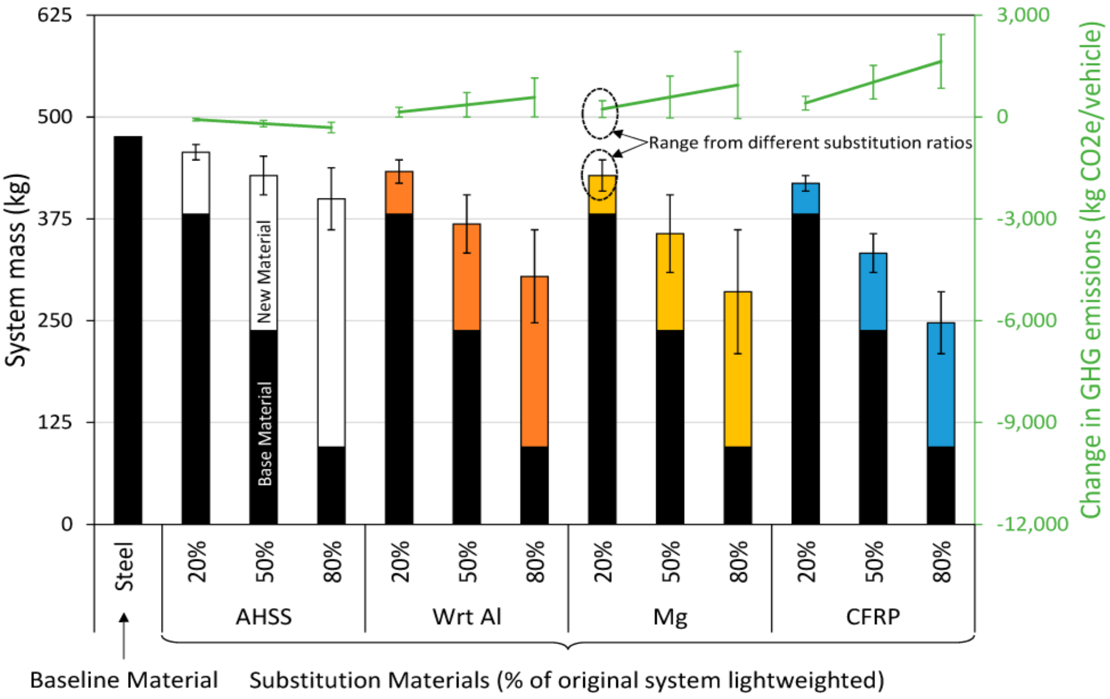


Figure 1.2 Impact of substitution material on system mass and GHG emission (Kelly et al., 2015)

In light weight design, designers exploit the strength of different material and join them together to form a high performance yet low weight product. Aluminium and polymer are two common light weight material which have been widely used in automotive industry because they are capable to reduce weight significantly while enhancing performance and safety (Hirsch, 2014). However, due to the difference in mechanical properties and thermal properties between the materials, special requirement in term of joining method is required to join the dissimilar material together.

The joining method can be classified into three categories, which are thermal joining, chemical joining and mechanical joining. Thermal joining methods are generally not suitable for joining metal to polymer owing to the thermal properties different between them, and chemical joining methods are less preferable due to the fact that it requires long surface preparation and curing time and it is not environmental friendly. Besides, the chemical bond strength might degrade due to exposure to high temperature for a prolong time (Okba et al., 2017).

Hence, mechanical joining is the most suitable way in forming metal-polymer hybrid joint. The most common mechanical joining method is fastener joining, it can be used when disassembly is required. But, this kind of joining method requires pre-drilled hole prior to the process. It also introduces extra weight to the assembly and causes stress concentration around the joint.

Apart from fastener joining, there are other mechanical joining methods which are more feasible in creating hybrid joint, and they are clinching and self-pierce riveting. By utilizing plastic deformation, the process plastically deformed the lower and upper sheet material and joined them together by the interlock formed between them. As compared to self-pierce riveting, mechanical clinching offers additional advantages such as cost reduction, weight reduction, faster process and less joining force. However, the success of the hybrid joint formation process is highly dependant on the properties of the materials to be joined , type of die being used and the punch load being applied (Lambiase, 2015a). Thus, selection of materials, design of the clinch tools and joining force are crucial in determining the success of the joint formation.

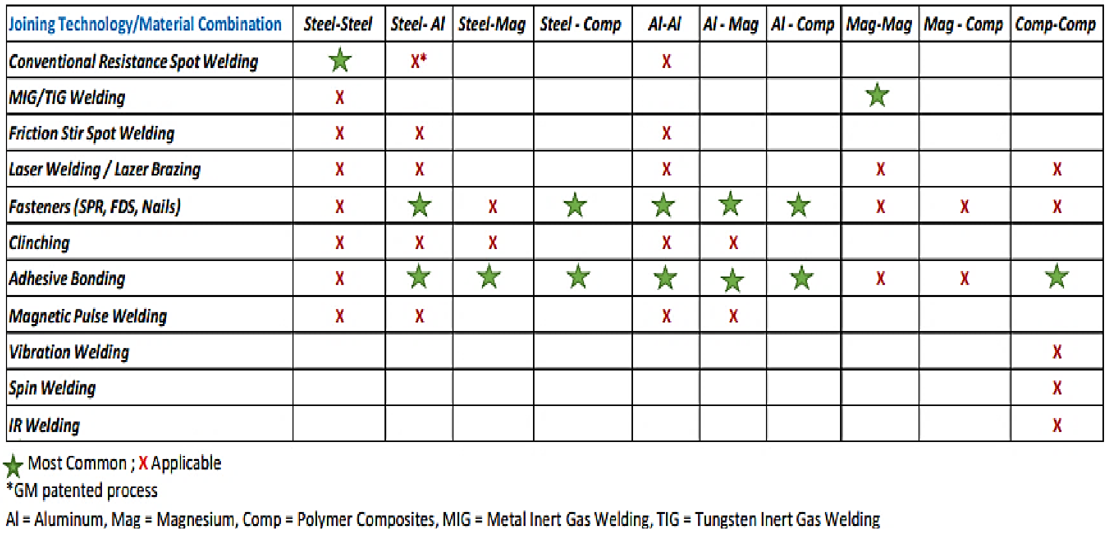
1.2 Importance of the Study

The findings of this study may have huge impact on providing industry a simple, economical and environmental friendly joining method to join dissimilar material together. This study will also provide better understanding and knowledge on:

- Suitability of using round grooved clinch die to form hybrid joint.
- The effect of materials selection and joining force on joint formation, joint strength and failure mode.
- How to simulate clinching process by using finite element method.

1.3 Problem Statement

Dissimilar materials are commonly being joined together to form hybrid material assemblies. It exploits and utilizes the advantages of each material and represent a key method in enhancing product's performance while minimizing the overall weight of the product (Sakundarini et al., 2013). However, joining dissimilar material such as metal and polymer is very challenging because of the huge difference in mechanical properties and thermal properties between them (Martinsen, Hu and Carlson, 2015). Clinching can be the solution to address this problem. However, it has not gained too much attention from the industry in producing such metal-polymer hybrid joint (Stevens, 2017). This is because there are limited studies on the feasibility of joining polymer with metal with clinching method. Figure 1.3 shows the commonly used and applicable joining method in automotive industry.



Joining Technology/Material Combination	Steel-Steel	Steel- Al	Steel-Mag	Steel - Comp	Al-Al	Al - Mag	Al - Comp	Mag-Mag	Mag - Comp	Comp-Comp
Conventional Resistance Spot Welding	★	X*			X					
MIG/TIG Welding	X							★		
Friction Stir Spot Welding	X	X			X					
Laser Welding / Lazer Brazing	X	X			X			X		X
Fasteners (SPR, FDS, Nails)	X	★	X	★	★	★	★	X	X	X
Clinching	X	X	X		X	X				
Adhesive Bonding	X	★	★	★	★	★	★	X	X	★
Magnetic Pulse Welding	X	X			X	X				
Vibration Welding										X
Spin Welding										X
IR Welding										X

★ Most Common ; X Applicable
*GM patented process
Al = Aluminum, Mag = Magnesium, Comp = Polymer Composites, MIG = Metal Inert Gas Welding, TIG = Tungsten Inert Gas Welding

Figure 1.3 commonly used and applicable joining method in automotive industry (Stevens, 2017)

Besides, (Lambiase, 2015a) conducted a test to study the joinability of aluminium with polycarbonate by using different clinch die which included round grooved, round split, flat and rectangular die. In his paper, he concluded that, round grooved clinch dies are not suitable to be used for joining aluminium with polymers regardless of its diameter and the joining force applied.

Thus, the questions remain are: is round grooved clinch die really not suitable for forming hybrid aluminium-polycarbonate joint? Is round grooved clinch die also not suitable for joining aluminium with polymers other than polycarbonate?

1.4 Aims and Objectives

The overall aim of this study is to determine the feasibility of joining aluminum with polymers by using round grooved clinch set. The specific objectives of this study are to:

1. Perform numerical simulation on clinching process by using finite element analysis (FEA) and correlate the result with experimental result.
2. Determine the formability of Al5052-polymer hybrid clinch connection by using round-grooved clinch set.
3. Study the effect of punch load on the success of joint formation.
4. Study the mechanical behavior of hybrid connections formed.

1.5 Scope and Limitation of the Study

The scope of this project is to determine the joinability of some commonly used polymers such as Polycarbonate, Polyvinyl Chloride and High Impact Polystyrene with Aluminium 5052 by using round grooved clinch set, determine suitable joining force and assess mechanical behaviour of clinch connection formed by means of single lap shear test.

The limitation of this study are as follows:

- The quality of the tensile specimen plays a crucial role in determining the quality of material characterization result. Injection and compression molding are more suitable in producing plastic specimen. However, the tensile specimens used in this research are produced either by CNC or laser cutting.
- There are a variety of round grooved clinch tool designs available in the market and the mechanical behaviour of the clinch joint is highly dependent on the clinch tool design. In the present research, only one type of round-grooved clinch tool set was used in the study.
- In Finite element analysis, mesh size plays a crucial role in determining the accuracy of the result. However, mesh size is a trade-off between accuracy and computing time, smaller mesh size means longer computing time. Thus, an adequate mesh size was selected after taking computing time into consideration.

1.6 Contribution of the Study

The findings of this study justify and provide industry better understanding on the feasibility of using round grooved clinched die to form hybrid clinch connection between Aluminium 5052 and polymers. It also provides industry the knowledge of the effect of punch load on joint strength and failure mode and that in turn helps the industry to select proper punch load and prevent undesired failure. The numerical simulation method introduced in the study will also provide industry better understanding on clinching simulation process and help industry to minimize experimental cost and predict potential failure.

1.7 Arrangement of the report contents

This report consists of five chapter, the first chapter covers the general background of the study, highlights the importance of the study, points out the limitations of previous study, identify aim and objectives of the study and also elaborates the scope and limitations of this study.

Chapter two is the literature review which reviews, compares and contrast other researchers related studies.

Chapter three elaborates the method and approaches that were used in the study to achieve the aim and objectives.

Chapter four presents the findings and results obtained from both simulation and experiment. All the key findings were also discussed and interpreted in this chapter.

Lastly, conclusion and recommendation were made in chapter 5.

CHAPTER 2

LITERATURE REVIEW

2.1 Introduction

Lightweight design exploits the superiority of different material and assemble them together to create a functional product with minimum weight. It requires joining process to bring the separate components together. The Joining method can be classified into three categories, which consist of thermal joining, chemical joining and mechanical joining. However, not every joining method are suitable for joining dissimilar materials, because each material possesses different properties such as mechanical properties, thermal properties and chemical properties. Therefore, there is the need of special joining method to join dissimilar material together. Recently, there are numbers of researches have been conducted to determine suitability of different joining method in joining dissimilar material and also parameters that affect the performance of the joint. Martinsen, et al. (2015) summarized and compared numbers of joining technique which are capable in joining dissimilar materials. Ozdemir and Oztoprak (2017) investigated the behaviour of adhesive joined structure under different condition. Goushegir (2015) presented the capability of friction spot joining method in joining dissimilar materials. Min, et al. (2014) studied the feasibility of friction stir blind riveting in joining dissimilar materials and effect of the operating condition on its joint strength. Lambiase and Di Ilio (2015) investigated the suitability of clinching process in producing polymer-metal joint. Lambiase (2015) further studied the effect of different thermoplastic on clinch joint performance. Lee et al. (2010b) investigated the effect of process parameters on the formation of hybrid material clinch joint. In this chapter, the approach, feasibility and essence of the previous studies will be reviewed and analysed.

2.2 Light weight design

Owing to the increasing awareness over environmental protection and resources scarcity, light weight design concept has gained a lot of interest from designers and engineers. In this concept, low density yet high performance-to-weight ratio material is preferable and is used to replace heavy metal such as steel. The total number of parts in the assembly will also be minimized to reduce the weight of the entire structure.

With this, the consumption of raw material and energy can be significantly reduced and subsequently improve the product performance as well as reduce GHG emission. Aluminium alloy and polymer are two ideal lightweight materials. They have been widely used in many industries because of their high strength to weight ratio, machinability and availability. Besides, Hirsch (2014) presented the recent development and increasing application of aluminium in automotive industry. Patil, Patel and Purohit (2017) also gave a comprehensive review about high performance polymer and their application in vehicle. This shift of material from steel to aluminium and polymer, and also the increasing use of multi-material structure trigger the need of new joining technique which are capable in joining dissimilar material efficiently.

2.3 Related research on method used to join dissimilar materials.

Joining dissimilar material together is challenging due to the differences between the material properties such as mechanical properties, thermal properties and electrical properties. To date, there are numbers of joining method has shown its capability in creating sound hybrid material joint or even have been widely used in industry. These methods are chemical adhesive joining, friction spot joining, mechanical joining with frictional heat and mechanical joining with plastic deformation. The joining process and its performance and limitation in joining dissimilar material ise reviewed and discussed in the following section.

2.3.1 Chemical adhesive joining

Adhesive bonding is one of the most commonly used joining method in automotive and aerospace industry (Grant, Adams and da Silva, 2009). It can be used to join dissimilar material without adding much weight on the structure. Besides that, it also offers several advantages such as low cost, distribute the stress evenly without causing stress concentration area, create a seamless joint and act as a barrier to prevent chemical reaction between two material (Pramanik et al., 2017). However, adhesive bonding is an irreversible process, attempt to disassemble may be difficult and costly. Besides, the adoption of adhesive bonding required surface preparation prior to the joining process, and the adhesive strength will degrade under excessive thermal exposure for a prolong time (Okba et al., 2017).

2.3.2 Friction spot joining

Friction spot joining is another method that capable in joining dissimilar material. This method requires multiple non-consumable independent parts and numbers of steps to form a sound joint. Firstly, it plasticises the metal part by heat which result from friction between the metal surface and rotating tool. Then, the soften metal flows into a reservoir which left behind by retraction of the pin. After that, the plasticised metal is pushed against by pin and formed a metallic nub with undercut geometry to interlock two material together. Figure 2.1 shows the schematic diagram of friction spot joining technique. This method does not require additional material and does not introduce extra weight to the structure. However, it has many independent moving parts which makes the automation process complex. In addition, Goushegir (2015) stated that hybrid joint formed by this method has low torsion and weak peeling strength.

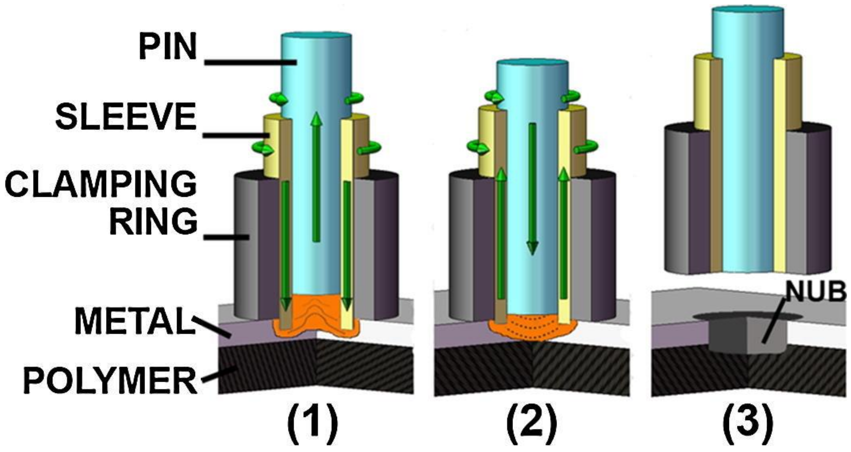


Figure 2.1 Schematic diagram of Friction spot joining technique (Goushegir, 2015)

2.3.3 Mechanical joining with frictional heat

Apart from adhesive joining and friction spot joining, polymer-metal hybrid joint can also be formed by mechanical joining with the ease of frictional heat. For example, flow drill screw and friction stir blind riveting. Unlike fastener joining and conventional riveting, these methods do not require predrilled hole. They utilize the frictional heat which generated from the rubbing of rotating component on material surface to soften the material so that the joining component can be driven through the material easily without the needs of pre-drilled hole. In the fiction stir blind riveting process, after the blind rivet penetrated the lower layer material, the blind rivet is upset using the mandrel to create an interlock as conventional rivet. Figure 2.2 illustrates the schematic diagram of friction stir blind riveting process. These methods do not require pre-processing and simplified the automation process but they introduce extra weight to the structure. Besides, the feasibility of the method are highly depends on the mechanical and thermal properties of the materials (Min et al., 2014).

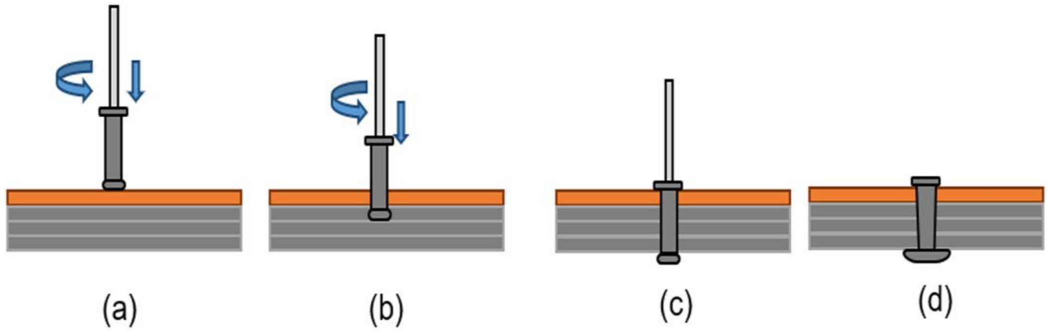


Figure 2.2 Schematic diagram of friction riveting technique (Khan, Wang and Li, 2018)

2.3.4 Mechanical joining with plastic deformation

Joining by plastic deformation does not require thermal effect, it utilise the formability and ductile behaviour of the material and induce a material flow to create an interlock between materials. It does not require surface preparation and can be used to join wide range of material as well as dissimilar material. Self-pierce riveting and mechanical clinching are two common examples of mechanical joining by plastic deformation.

In a self-pierce riveting joining process, a hollow tubular rivet is driven through the upper sheet and through the reaction of counter die, the skirt of the tubular rivet deformed and inserted into the lower sheet to form an interlock (Mori et al., 2013).

Whereas, for mechanical clinching, external joining component such as rivet and fastener are not required, sheets are joined together by local hemming with a set of die and punch. The hemming process induced a material flow and formed an interlock between two materials. The formation of the interlock is due to the different degree of plastic deformation of two materials (Mori et al., 2013). Figure 2.3 shows the formation of interlock between two materials by clinching process. Since it does not requires extra material it offer extra advantages such as weight reduction, faster process, lower fatigue strength and lower running cost (Mori, Abe and Kato, 2012).

Apart from weight reduction and cost reduction, mechanical clinching also offers several advantages over other competitive joining method. First, it is cleaner and more environmental friendly because it does not require any chemical for pre-treatment and it does not produce any waste product such as fume and scrap throughout the process. Besides, this method is simple and does not involve any rotational component, so that it can be automated easily and has high repeatability.

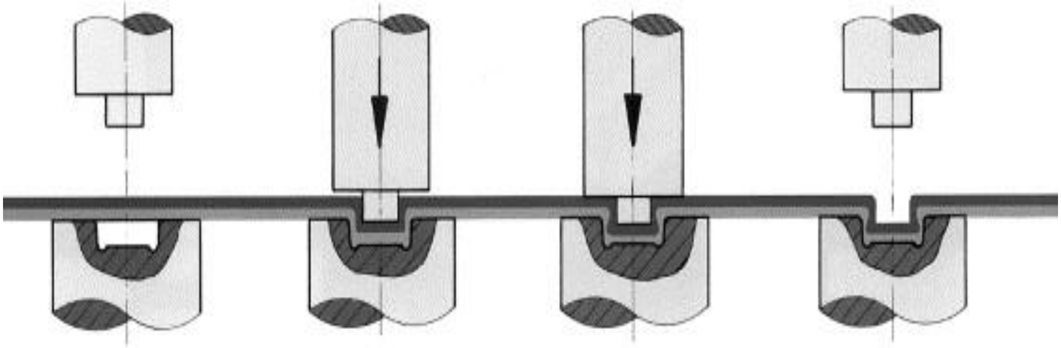


Figure 2.3 Schematic diagram of clinching process (Varis, 2006)

2.4 Processing Condition and Geometry parameters

2.4.1 Effect of joining force on joint formation

Joining force is one the crucial processing condition in determining the success of the clinching process. The required force is depending on the material to be joined and the parameters of the tools. As reported in (Lambiase and Di Ilio, 2015), the magnitude of force will affect the load carrying capability of the joint and results different failure modes. when the joining force is low, metal interlock will not form and the structure tends to fail by button separation; besides, if the joining force is too high, the metal sheet might crack and fail by fracture. Figure 2.4 depicts the influence of joining force on the failure modes.

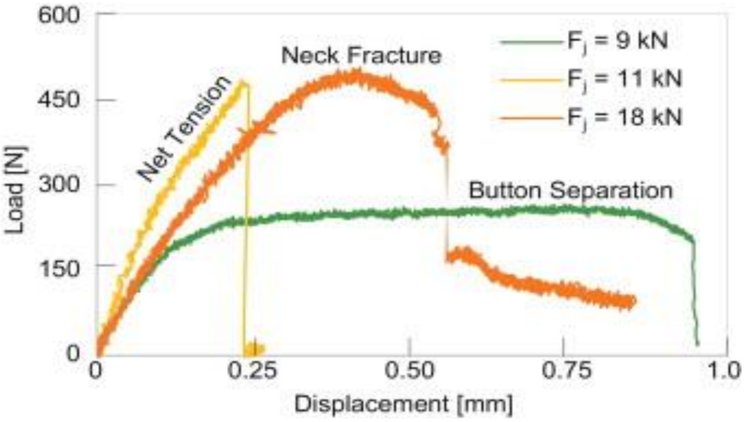


Figure 2.4 Load - displacement curve of joint formed under different joining force (Lambiase and Di Ilio, 2015)

2.4.2 Effect of material types on joint

Numbers of research have been conducted to test the joinability of different polymer with metal by clinching method. Lambiase (2015) studied the joinability of polycarbonate (PC), polymethyl methacrylate (PMMA) and polystyrene (PS) with aluminium by mechanical clinching. Lambiase, Durante and Ilio (2016) reported the feasibility of joining glass fibre reinforced polymer (GFRP) with aluminium. Lambiase and Ko (2016) further studied the joinability of carbon fibre reinforced polymer (CFRP) with aluminium by clinching. It is reported that the toughness of the materials is important for the success of the joint formation. Materials with high toughness are easier to join when compared to low toughness materials since they do not break easily in the joining process. Besides that, the properties of the material also affect the load carrying capability of the hybrid joint. Figure 2.5 depicts the influence of material selection on load carrying capability of hybrid joint.

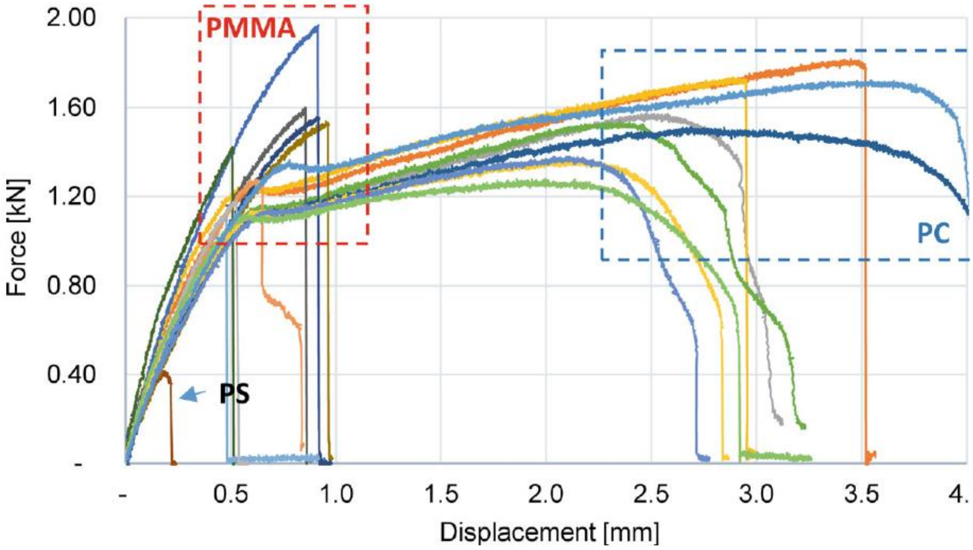


Figure 2.5 single lap shear test force - displacement curve different materials (Lambiase, 2015a)

2.4.3 Effect of clinching tools on joint formation

Lambiase (2015b) compared the mechanical behaviour of the hybrid joint formed by different clinch tools. In the study, Polycarbonate-Aluminium hybrid joint formed by different clinch tools such as round grooved, round split, round flat and rectangular die were studied and compared. Figure 2.6 depicts the different types of clinching tools used. It is reported that round grooved die is not feasible for joining aluminium with polymers regardless the punching load applied and the diameter of the die used for the process, it failed to form a sound joint because the polymer bulge was torn out from the polymer sheet in the offsetting process. Besides, split die with deep die anvil also failed to join the sheets together due to the shearing of metal button. Apart from these, the remaining tools are able to form sound joint. The joints formed were tested with single lap shear test and gave the result as shown in Figure 2.7 a & b. Based on the results, it can be noticed that, rectangular dies are able to formed sound joint with lowest joining force as compared to other types of die, while round split die and round flat die required higher joining force to form a sound joint. This was ascribed to reduction of hydrostatic stress due to the shearing effect. But, the increase of joining force from 7.2 kN to 18 kN for rectangular die gave a negligible change in shear strength. On the other hand, round dies were able to produced strongest hybrid joint due to the absence of fracture. The increase of joining force allowed the produce of large interlock and in turn increase the shear strength.

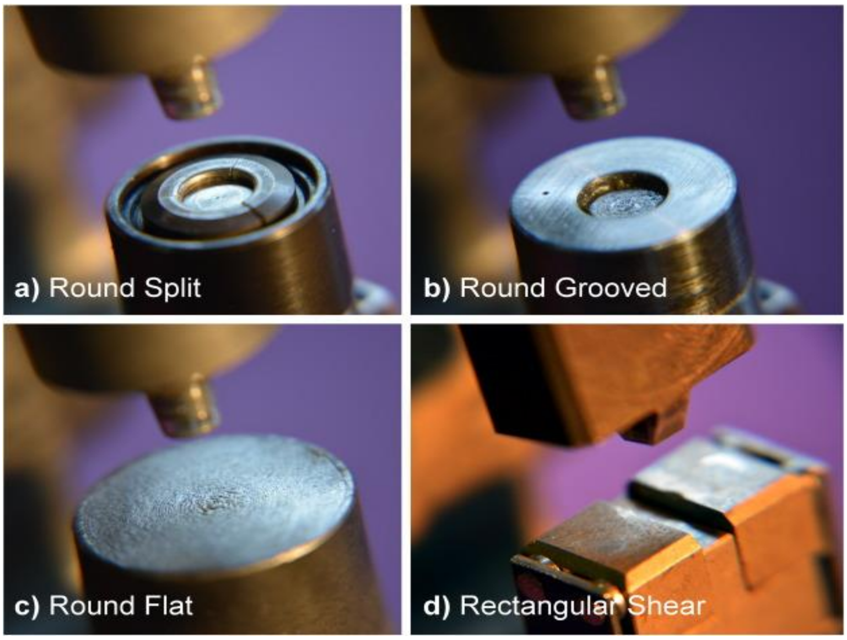


Figure 2.6 Types of clinching tools adopted (Lambiase, 2015b).

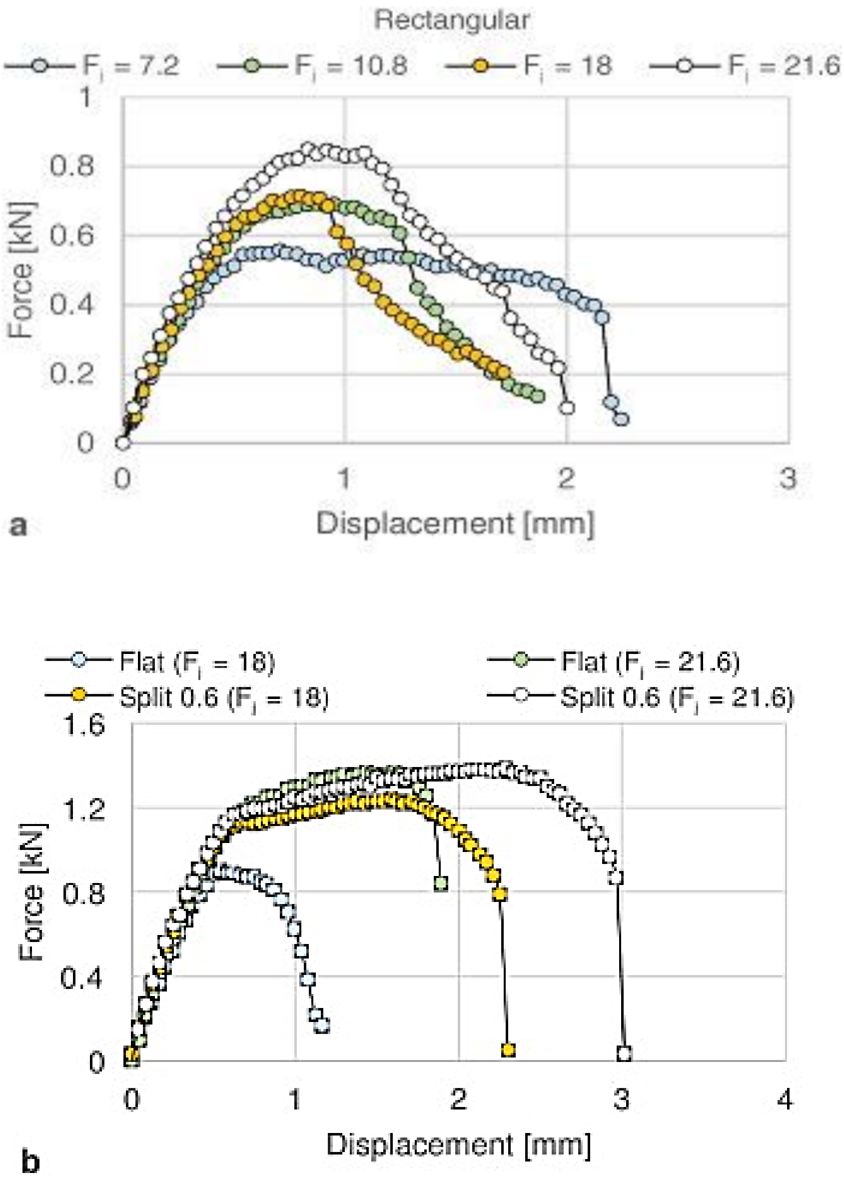


Figure 2.7 a & b single lap shear test force-displacement curve of hybrid joint produced with different types of dies and joining force, F_j (Lambiase, 2015b)

2.5 Tool design

Apart from joining force and joining material, tool design also plays a vital role in determining the success of joint formation. It also affects the tool service life, joining forced required and joint strength. A proper designed tool can increase the service life of tools, enhance the joint strength and reduced the required joining force which in turn reduce the energy consumption. As reported by Mucha (2011), the required joining force can be reduced by increasing the die groove width W_g, this is because, larger groove generates lower material flow resistance and reduce the forming resistance in the limited material displacement condition. Besides, the increase of die groove width will also increase the thickness of the interlock formed. Figure 2.8 shows the effect of relative groove width on joining force, neck thickness,t_n, and interlock thickness,t_s.

Apart from that, the die radius is also a crucial parameters in determining the joinability. Lambiase and Ilio (2013) reported that the increase of punch radius improves the neck thickness and interlock thickness and consequently increase the joint strength and load carrying capability.

On the other hand, Lee et al. (2010b) investigated the effect of die depth and die radius on the joinability of the structure, and the joinability was evaluated by the neck thickness and interlock thickness. It is reported that the increased of die radius led to the increase in neck thickness. But, the formation of interlock was difficult when the radius of the die is too large. furthermore, the increase of die depth increased the interlock thickness and consequently increased the joint strength. However, crack was developed when the die depth was too deep. This is ascribed to the excessive thinning of the of the upper sheet. Figure 2.9 shows of the effect of die depth,H, and die radius,R_d, on joinability of hybrid structure.

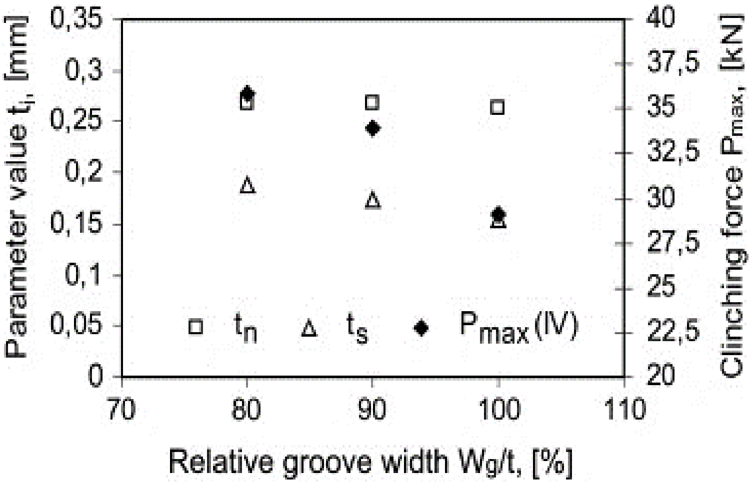


Figure 2.8 The effect of groove width on joining force, neck thickness ,t_n, and interlock thickness ,t_s (Mucha, 2011).

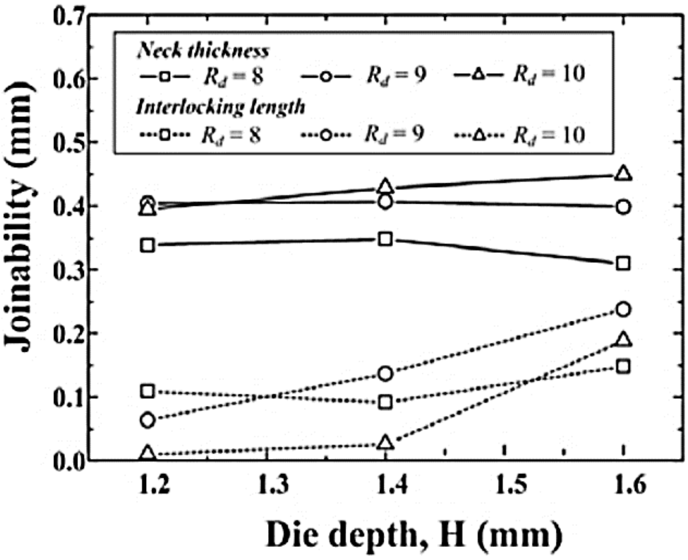


Figure 2.9 Effect of Die parameters on joinability (Lee et al., 2010b)

2.6 Failure modes

Hybrid clinch joint produced on different material combination under different joining force fails by different failure modes. The failure modes included button separation, neck fracture and polymer failure.

2.6.1 Button separation

Button separation is typical failure occurs on hybrid structure with insufficient interlock. Small interlock or absent of interlock can be caused by improper clinch tools design, huge strength differences between upper and lower sheet (Abe, Mori and Kato, 2012) and insufficient joining force (Lambiase and Di Ilio, 2015). If the die side sheet has much higher strength as compared to punch side sheet, the die side sheet will exert high hydrostatic stress on the punch side sheet and restrain flow of the material, and therefore limit the formation of undercut. As a result, the clinch joint formed will have large neck thickness but small interlock. This type of failure is characterized by low load carrying capability as the bulge formed can be pulled out easily when shear force was applied. Figure 2.10 illustrates the button separation failure for clinched joint.

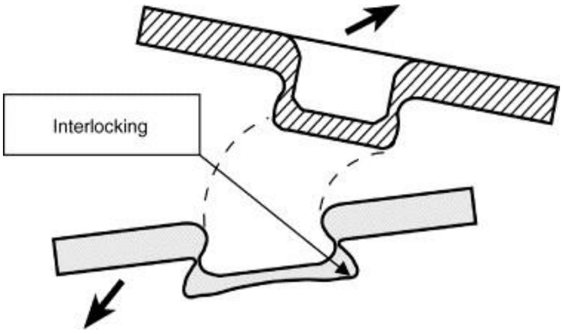


Figure 2.10 Schematic diagram of button separation (Varis, 2006)

Besides that, Lee et al. (2010) applied free body equilibrium method to evaluate the load required to unbutton the joint. Figure 2.11 shows the free body diagram of clinch joint used in the evaluation process. In the analytical model, the circular arc and spline of the clinched connection were assumed to be a linear line, and the yield stress of the punch side sheet was assumed as average flow stress. The force required to unbutton the joint, F_B, can calculated by equation 2.1.

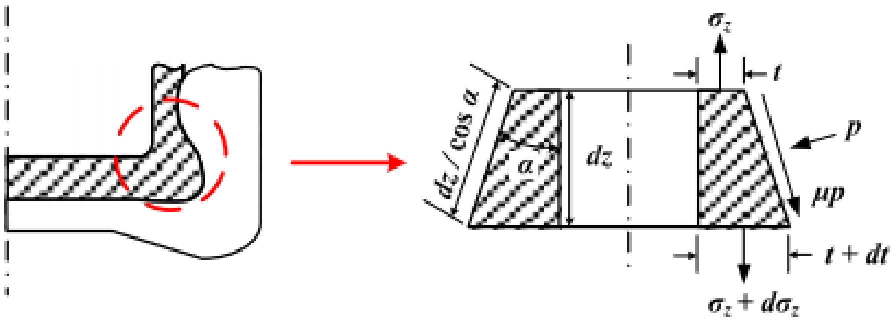


Figure 2.11 Free body diagram of clinched joint (Lee et al., 2010a)

$$F_B = \pi \cdot (2R_P t_N + t_N^2).\bar{\sigma}_Y \left(\frac{1 + \frac{\mu}{\tan\alpha}}{\frac{\mu}{\tan\alpha}} \right) \left[1 - \left(\frac{t_N}{t_U + t_N} \right)^{\frac{\mu}{\tan\alpha}} \right] \qquad (2.1)$$

Where

$\bar{\sigma}_Y$ = Average flow stress, Pa

t_U = Length of the undercut, m

μ = Friction coefficient

2.6.2 Neck fracture

In the clinching joining process, the higher strength or thicker material is preferable to be located on the punch side as the punch side sheet undergoes more plastic deformation. However, if the die side sheet has too little strength and unable to exert sufficient hydrostatic pressure on the punch side sheet, neck fracture as depicted in Figure 2.12 is likely to occurs. This type of failure happens more readily in metal-polymer hybrid structure than metal-metal structure because of the huge strength difference between materials and low enveloping effect polymer sheet able to exert on the metal sheet (Lambiase and Di Ilio, 2015). Besides that, Lambiase et al. (2016) also stated that excessive die anvil depth and excessive thickness of lower sheet will also reduce the neck thickness and promote neck fracture failure. Hybrid joints with partial neck fracture are still capable in carrying load, but its fatigue behaviour and corrosion resistance are highly compromised (Lambiase, 2015a).

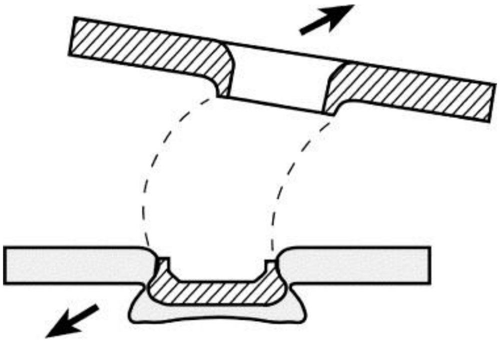


Figure 2.12 Schematic diagram of neck fracture (Varis, 2006)

According to Lee et al. (2010), neck fracture occurs when the stress reaches the fracture stress, $\overline{\sigma_f}$, and the fracture load, F_N, can be calculated by equation 2.2

$$F_N = \overline{\sigma_f} \, . A_N = \pi . (2R_P t_n + t_n^2) . \overline{\sigma_f} \qquad (2.2)$$

Where

$\overline{\sigma_f}$ = Fracture stress of upper sheet, Pa

A_N = Projection area of the neck, m^2

R_P = Clinching Punch radius, m

t_n = Neck thickness, m

For the metal-metal joint, neck fracture is less likely to occurs as the lower metal sheet able to exert sufficient hydrostatic force to restrain the material flow and prevent excessive thinning of the bulge neck. However, the joint might still be failed by metal fracture such as radial crack if improper joining force is applied. Figure 2.13 shows the fracture of metal bulge due to the excessive tensile hydrostatic stress generated during punching process.

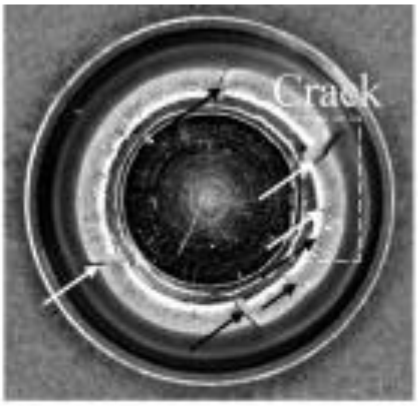


Figure 2.13 Metal fracture on lower sheet (Mori and Abe, 2018)

2.6.3 Polymer failure

Polymer failure can be categorized into two types, namely net tension and pull out. Net tension is a common failure mode occurs on clinch connection formed with low toughness material which crack easily without plastically deformed (Lambiase, 2015a). This type of failure will occur suddenly and lead to sudden loss of load carrying capability. Figure 2.14 illustrates the failure of clinch connection occurred due to net tension. One of the measures can be taken to solve this problem is through pre-heating process. With proper pre-heating, the toughness of the material can be improved, and the crack development can be prevented. However, excessive preheating might results excessive softening of polymer and lead to reduction of interlock (Lambiase and Di Ilio, 2015).

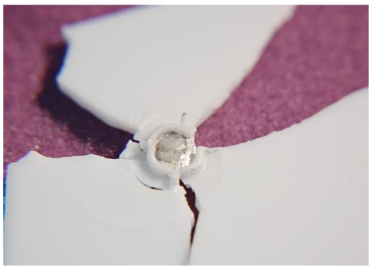


Figure 2.14 Net tention failure (Lambiase, 2015a)

Next, another type of polymer failure is pull out failure, it is a failure mode occurs on clinched connection formed between two material with high difference in strength (Lambiase, 2015b). The hybrid connection fails due to high bearing load deforms the polymer sheet preceding the pull out of metal bulge from polymer button. Figure 2.15 illustrates the pull-out failure occurs during single lap shear test.

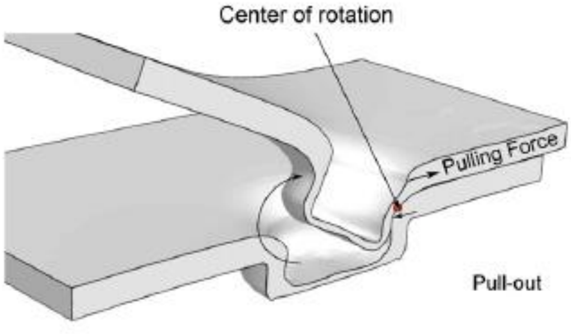


Figure 2.15 Pull out failure (Lambiase, 2015b)

The average bear stress can be calculated as equation 2.3 as follow:

$$\sigma_b \cong \frac{F_s}{H_R \times (d + 2t_n + t_s)} \tag{2.3}$$

Where
σ_b=Average bear stress, Mpa
F_s= External load, kN
H_R= Bulge height, mm
d= Bulge inner diameter, mm
t_s= Interlock thickness, mm

Then, the maximum bearing load of the clinched connection can be calculated by equation 2.4 as follow:

$$MBL = \sigma_y . H_R \times (d + 2t_n + t_s) \tag{2.4}$$

Where
MBL= Maximum bearing load, kN

2.7 Summary

To sum it up, light weight design and multi-material design concept are trending up in many industries. They represent a feasible solution to achieve weight reduction, higher performance, lower fuel consumption and lower GHG emission. These design concepts utilize the strength and exploit the superiority of each material and join them together to form a high performance yet low emission product. However, joining dissimilar material is difficult due to the difference in mechanical and thermal properties for each material. To date, there are number of researches have been conducted to study the feasibility of different joining method in joining dissimilar material. Among all of the competitive joining technique, mechanical clinching represents a more feasible method for joining dissimilar materials as it offers extra advantages such as simple, cost-effective, eco-friendly and weight reduction. However, round grooved clinch tool is reported to be not suitable for joining aluminium with polymers regardless of its diameter and the joining force applied.

On the other hand, different failure modes were reportedly occurred during the single lap shear test of clinched connections. These failures included button separation, neck fracture, pull out and polymer fracture, and the stem of such failures included inadequate joining force, improper material selection and bad tool design. Thus, in the presence study, the effect of joining force and polymer selection on the strength of hybrid material clinched connection were studied.

CHAPTER 3

METHODOLOGY AND WORK PLAN

3.1 Introduction

The main objective of this project is to study the feasibility of joining polymer with aluminum 5052 by using round grooved clinch tool. A sequence of works and steps are required and were carried out to achieve this aim. At the very beginning of the project, aluminum 5052 and polymers testing specimens were prepared according to ASTM E646-98 and ASTM D648 respectively by using SIEG PX-1 CNC milling machine. After that, the mechanical properties of the specimens were assessed by the means of uniaxial tensile test. The test was conducted by following ASTM standard procedure using Instron 5582 series universal testing machine with a load frame of 100kN. The results were then output from the tensile machine to computer and processed with Instron Bluehill Universal software, and the raw data was extracted and used to construct stress strain curve by using Microsoft excel. The stress strain behavior of the polymers and aluminum 5052 were studied and characterized.

Polymers with adequate toughness and strength were selected, prepared and joined together with aluminum 5052 by clinching process. The clinching process was performed on Instron 5582 series testing machine with round grooved clinch tool set which consist of holder, punch and die. During the clinching process, data such as punching load and stroke were collected. After sound hybrid connections was produced, its mechanical behavior was tested by means of single lap shear test (SLST) with Instron 5582 series testing machine. The load carrying capability and failure modes for each hybrid connections were observed and recorded.

For the simulation, finite element analysis software, Abaqus was used to simulate the clinching process. In the simulation process, round grooved clinch tools were 3D modelled and assembled, the stress-strain raw data obtained from the Instron Bluehill Universal Software was processed and input to define material properties, simulation operation setting such as boundary condition, steps and interaction were defined and analysis job was configurated and submitted. After the analysis job was completed, stress distribution contour plot and deformed clinched connection geometry parameters data were obtained and analysed. Besides that, punching load versus stroke graph was also constructed and compared with experimental result.

3.2 Material Characterization

According to Lambiase (2015), toughness of polymer and the formability of aluminum alloy play vital role in producing a sound hybrid connection. Thus, to select a suitable polymer for producing hybrid connection by clinching method, the mechanical behaviors for both polymers and aluminum must be assessed prior to the material selection. The mechanical properties were tested by the means of uniaxial tensile method. According to ASTM standard, the best way to fabricate a standard plastic testing specimen is by injection or compression molding. However, due to the unavailability of molding machine, the testing specimen of aluminum and polymers were prepared by using SIEG PX-1 CNC milling machine and Laser cutting machine respectively. In the milling process, 5mm diameter Flat end mill tool was used as the cutting tool and the materials were cut at 30mm/min feed rate.

As the specimen quality are crucial in determining the quality of the result, the specimens were prepared slightly bigger than the ASTM standard dimension and further finished by using P320 sandpaper and followed by P800 sandpaper to ensure the surface integrity of the specimen. Figure 3.1 and Figure 3.2 show the ASTM standard dimension for aluminum and polymer specimen in mm.

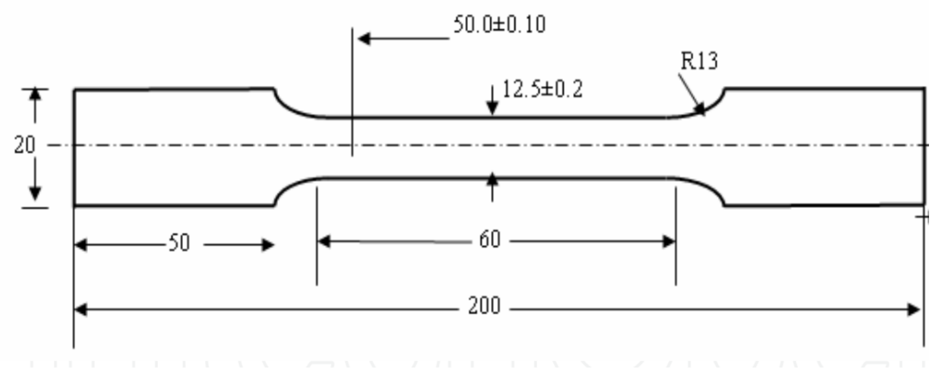


Figure 3.1 ASTM E646-98 Sheet Metal Specimen Dimension

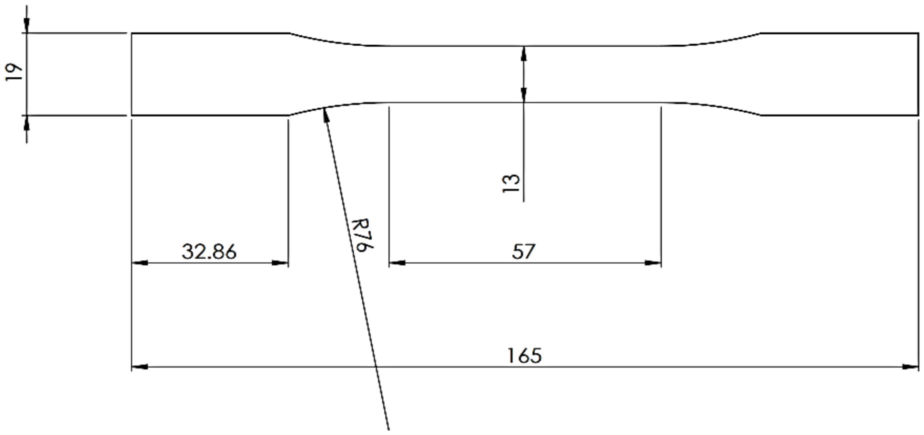


Figure 3.2ASTM D638 Sheet Plastic Specimen Dimension

Three tensile specimens were fabricated for each material as follows: polycarbonate (PC), polyvinyl chloride (PVC), high impact polystyrene (HIPS) and aluminium 5052. Figure 3.3 and Figure 3.4 show the tensile test specimen of polymers fabricated by laser cutting and Aluminium specimen produced by CNC milling respectively.

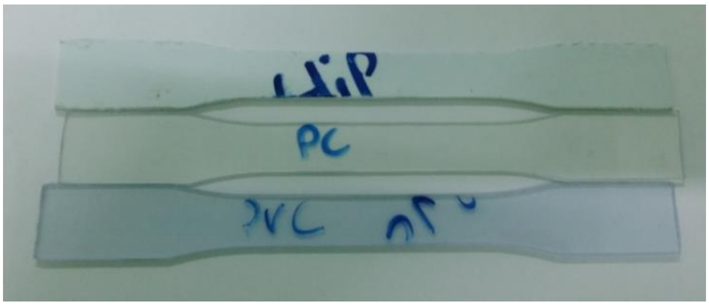


Figure 3.3 Polymers tensile specimen

Figure 3.4 Aluminium Specimen

After tensile specimen for each material was fabricated, uniaxial tensile test was performed on Instron 5582 series testing machine at 1mm/min constant pulling rate. Extensometer was located at the center of the specimen as shown in figure 3.5 to measure the change in length of specimen.

Figure 3.5 Setup of uniaxial tensile test

The Recorded data was processed and output as excel format raw data used to construct engineering stress strain curve. Figure 3.6 and 3.7 shows the engineering stress strain curve plotted.

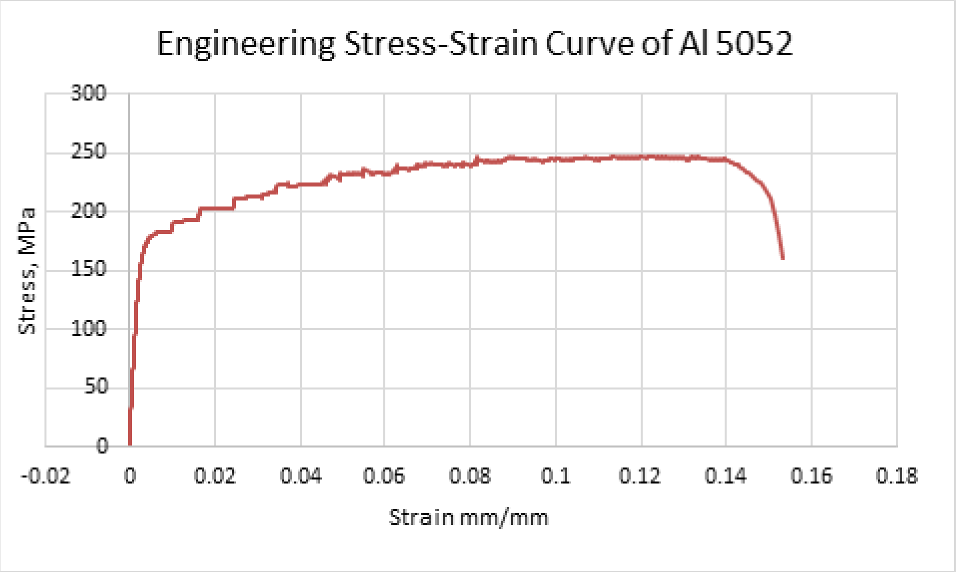


Figure 3.6 Engineering stress strain curve of Aluminium 5052

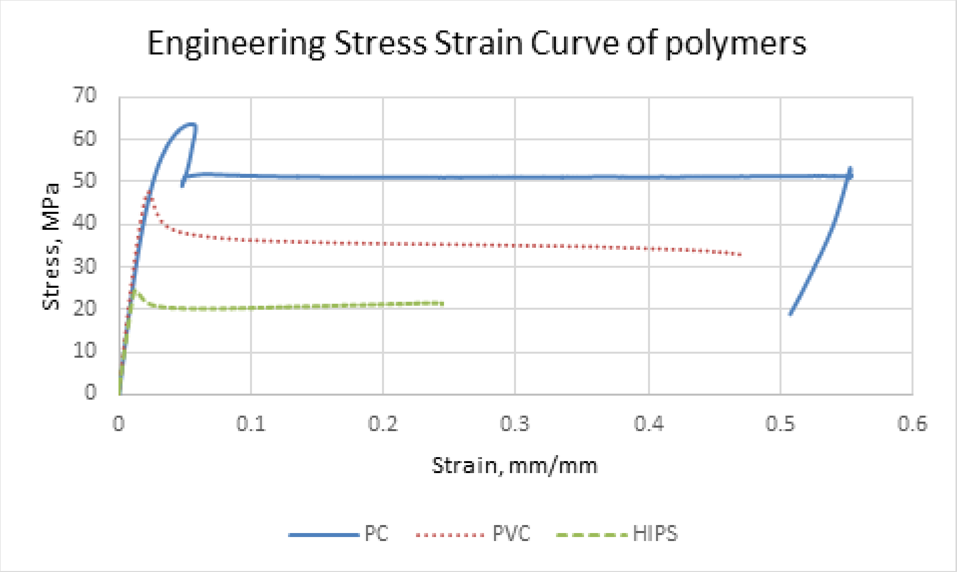


Figure 3.7 Stress Strain curve of PC, PVC and HIPS

3.3 Simulation

For the numerical analysis of clinching, Abaqus FEA software was being used to simulate the process. First and foremost, a 3D model of round grooved clinch set which consist of punch, die, holder and two material sheets was created as shown in figure 3.9.

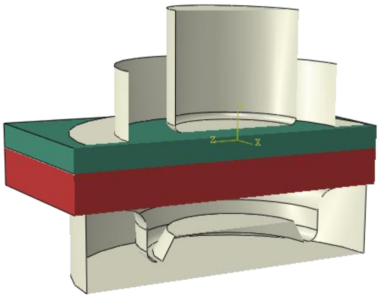


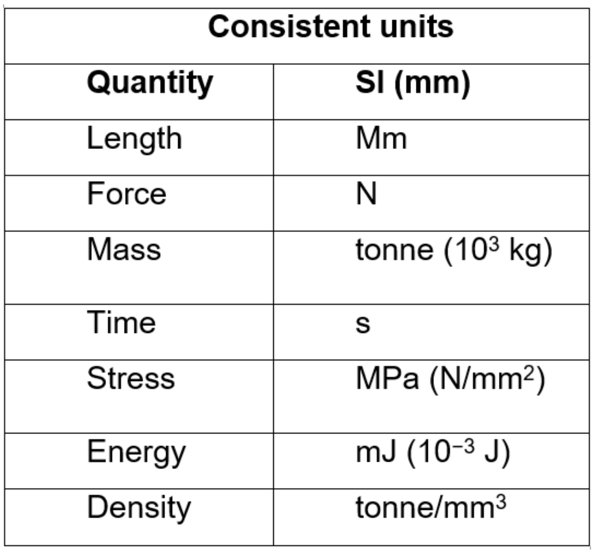
Figure 3.9 3D model of round grooved clinch set

After the 3D model was generated, in the component type setting, die, punch and holder were set as 3D discrete rigid whereas upper sheet and lower sheet were set as deformable body as the main focus of the simulation was to study the behavior of the two sheets during the clinching process.

After that, sets were created to represent geometry and collection of entities as it is required in defining simulation operation setting such as material properties assignment, boundary condition setting, parts interaction definition, history and field output request.

After the set was created, the material behavior such as density, Young's modulus, stress and strain were input and assigned to the specific set which represent the part. The data was input based on a set of self-consistent unit, which can be expressed in fundamental units without conversion factor, and this is because Abaqus do not has built-in unit system except for angle. In this simulation, SI unit in mm was used and the data was input according to the unit as shown in Table 3.1.

Table 3.1 Abaqus consistent units' conversion



Consistent units	
Quantity	**SI (mm)**
Length	Mm
Force	N
Mass	tonne (10^3 kg)
Time	s
Stress	MPa (N/mm^2)
Energy	mJ (10^{-3} J)
Density	tonne/mm^3

For the stress and strain input, the data are required to be input as trues stress and true strain. However, the raw data obtained from the tensile test is in the form of engineering stress and strain. Thus, conversion of engineering stress and engineering strain to true stress and true strain is required. The formula for converting engineering stress and strain to true stress and strain are shown in equation 3.1 and 3.2. The true stress strain curve for Aluminum 5052 and Polymers after the conversion are shown in Figure 3.10 and 3.11 respectively.

$$\sigma_{true} = \sigma_{engineering}(1 + \varepsilon_{\text{engineering}}) \tag{3.1}$$

Where

σ_{true} = True stress, Pa

$\sigma_{engineering}$ = Engineering Stress, Pa

$\varepsilon_{engineering}$ = Engineering strain, mm/mm

$$\varepsilon_{true} = \ln(1 + \varepsilon_{engineering}) \tag{3.2}$$

Where

ε_{true} = True strain, mm/mm

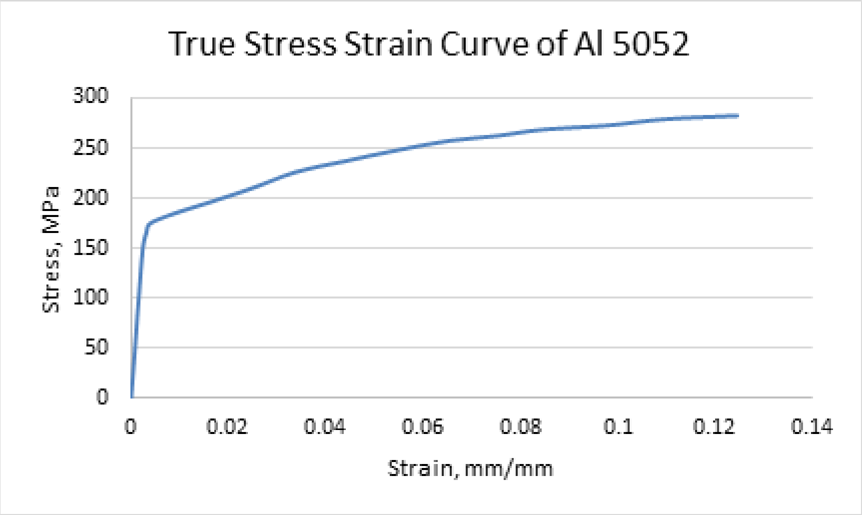


Figure 3.10 True Stress Strain curve of Aluminium 5052

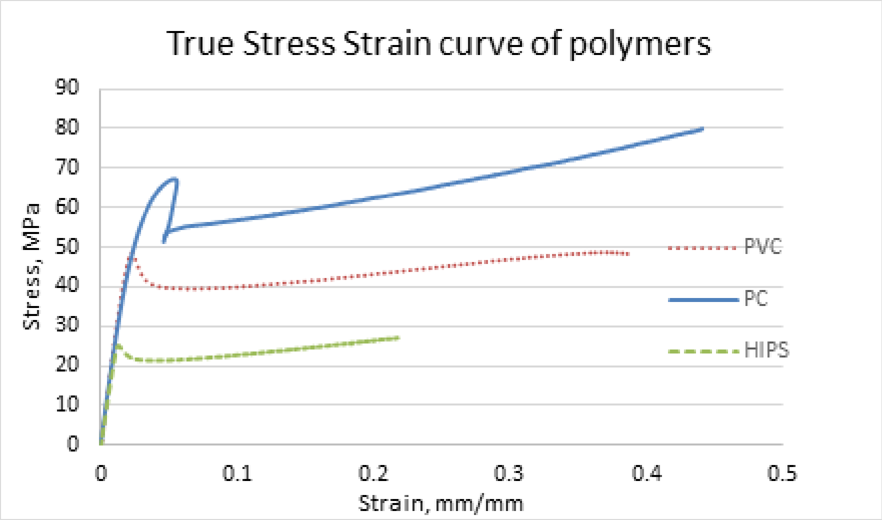


Figure 3.11 True Stress Strain curve of Polymers

Besides that, to include plasticity in Abaqus simulation, the data of the stress and strain after the yield strength are required and the data must be input in the form of trues stress and logarithmic plastic strain in ascending order. Thus, conversion of engineering strain in the plastic region to logarithmic plastic strain was performed. The engineering stress-strain data was taken from the lower yield point until the fracture point and converted to true stress and Logarithmic plastic strain by using equation 3.1 and equation 3.3. Figure shows the plastic region true stress strain curve.

$$\varepsilon_{\ln}^{plastic} = \ln\left(1 + \varepsilon_{engineering}\right) - \frac{\sigma_{true}}{E} \tag{3.3}$$

Where

$\varepsilon_{\ln}^{plastic}$ = Logarithmic plastic strain, mm/mm

$E = \frac{\sigma}{\varepsilon}$ =Young’s modulus, Pa

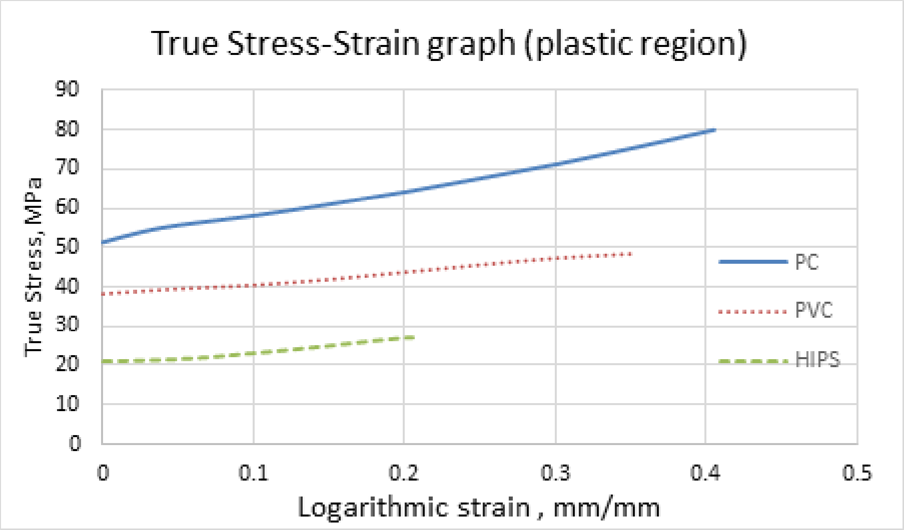


Figure 3.12 Plastic region true stress strain curve

After the material behaviors were defined and assigned to the respective parts, all parts were brought together to form an assembly. Position constraint such as face-to-face and coaxial were used to define the position relation between the parts. coaxial constraint was used to aligned circular parts so that they will have a common axis. Face-to-face constraint was used to ensure the selected faces of the parts is facing each other. Figure 3.13 shows the assembly of clinch set and Table 3.2 summarize the position constraints used for the assembly.

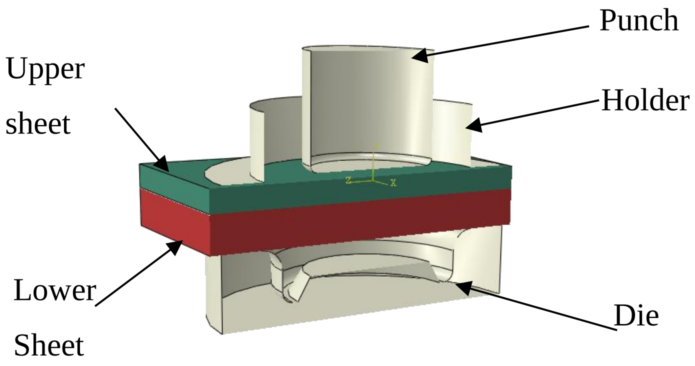


Figure 3.13 Assembly of clinch tool

Table 3.2 Summary of position constraints used

constraints	Parts
Face to Face	Die’s top surface to lower sheet’s bottom surface
Face to Face	Lower sheet’s top surface to Upper sheet’s bottom surface
Face to Face	Upper sheet’s top surface to Holder’s bottom surface
Face to Face	Upper sheet’s top surface to punch’s bottom surface
Coaxial	Die, holder, punch

After that, steps for the simulation process were created. There are only two steps in the clinching simulation. The first step is the initial step and the second step is punching step. The initial step defines the boundary condition and interaction between parts at the very beginning of the process, where the boundary condition of the die and holder were set as ENCASTRE, which means translation and rotation in X, Y and Z-axis of both die and holder is not allowed in this step. The second step is an analysis step that defined to represent punching step of the clinching process. In this step, boundary condition for die and holder was set as ENCASTRE while boundary condition for punch was set as Displacement/Rotation with U2 of -3.14, which means that the punch will be lowered -3.14 in Y direction during the analysis step.

Next, interactions were defined for the parts which come in contact with each other during the simulation. Surface-to-surface contact was chosen for the interaction definition to describes contact between a rigid surface and a deformable surface or between two deformable surfaces. Table 3.3 summarizes the surface chosen for surface interaction and the formulation selection used.

Table 3.3 Surface-to-surface interaction formulation

Interaction	First surface	Second surface	Mechanical constraint	Sliding formulation
Int.1	Die surface	Bottom surface of polymer	Penalty contact method	Finite sliding
Int.2	Bottom surface of Aluminum	Top surface of polymer	Penalty contact method	Finite sliding
Int.3	Holder surface	Top surface of aluminum	Penalty contact method	Finite sliding
Int.4	Punch surface	Top surface of aluminum	Penalty contact surface	Finite sliding

Lastly, the parts were meshed with a mesh size of 0.2. Explicit reduced integration hexahedra element mesh with linear geometric order was chosen as the element type. Besides, enhanced hourglass was used instead of default total stiffness formulation. This is because enhanced hourglass provides better mesh quality and performs better for non-linear response at high strain. Then, analysis job was created and submitted for numerical analysis.

After the analysis job was completed, stress distribution contour plot and deformed clinched connection geometry data were obtained and analysed. Punching load versus stroke curve of the process was also constructed to compare with experimental result.

3.4 Experiment

For experiment, polymers with adequate strength and toughness were joined together with Aluminum 5052 to form hybrid material structure by using clinching method. The process was performed on Instron 5582 series universal testing machine with round grooved clinch tool set at 1mm/sec punching rate. Figure 3.14 shows the setup of clinching process. During the clinching process, aluminum sheet was placed on punch side while polymer sheet was placed on die side. This is because punch side sheet will deform more as compared to the lower sheet (Lambiase, Durante and Ilio, 2016).

Figure 3.14 Setup of clinching process

Punching load from 10kN to 50kN were used to form the hybrid joint. Three samples were produced for each hybrid material combination (Al-PC, Al-PVC and Al-HIPS) at different punching load applied. During the process, load and stroke data were collected and used to construct punch load versus stroke graph. Figure 3.15 shows different views of clinched connection formed on Al-PC hybrid structure.

Figure 3.15 clinched connection on Aluminium-Polycarbonate hybrid structure (side, top and back view)

After sound hybrid connection was formed, its shear strength was assessed by means of single lap shear test using Instron 5582 series universal testing machine with load frame of 100kN at the control shear rate of 1mm/min. Figure 3.16 shows the schematic diagram of single lap shear test.

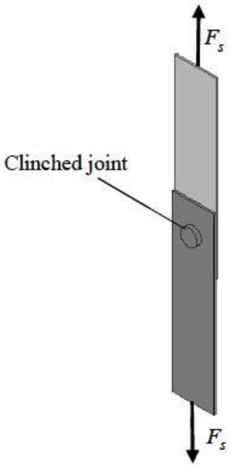


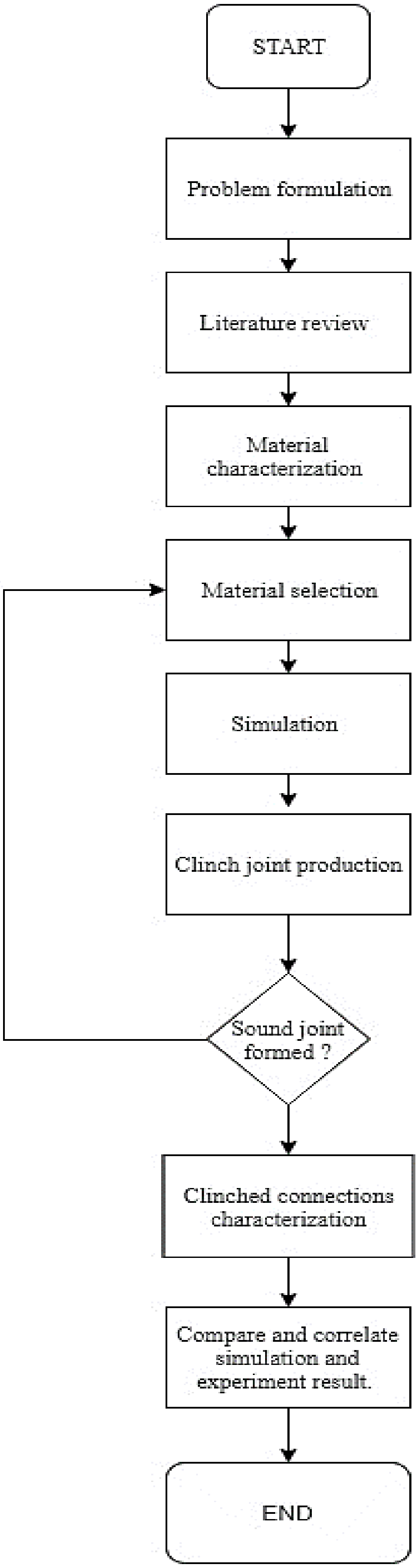
Figure 3.16 single lap shearing specimen

The shear strength and failure modes for each hybrid connections were observed and recorded. Lastly, experimental result such as clinched connection geometry and punch load-stroke curve was compared with numerical simulation obtained result to study the experiment-simulation correlation.

3.5 Summary

To achieve the objectives of the study, a sequence of work has been done. At the very beginning of study, material characterization process was performed, the material properties of aluminium and polymers were characterized by means of uniaxial tensile test with Instron 5582 series universal testing machine. After the material characterization process, suitable materials were selected and prepared for clinching process. In the clinching process, Aluminum 5052 was clinched with Polycarbonate, Polyvinyl Chloride and High Impact Polystyrene respectively by using round grooved clinch die at different punching load. The punch load versus stroke data was collected during the clinching process. All the sound clinch connections formed were tested with single lap shear test to assess its shear strength. The joint strength and failure modes of each clinched connection were recorded and analyzed. Meanwhile, numerical analysis was performed with FEA software- Abaqus to simulate the clinching process. The stress strain data collected from material characterization process was processed and input to software based on the format required. After all the required data has been input, analysis job created and performed. Stress distribution and final geometry of clinched connections were output and analyzed after the analysis job was done. Then, the simulation results were compared and correlated with experimental results to define numerical – experimental correlation.

3.6 Work plan


START
Problem formulation
Literature review
Material characterization
Material selection
Simulation
Clinch joint production
Sound joint formed ?
Clinched connections characterization
Compare and correlate simulation and experiment result.
END

CHAPTER 4

RESULTS AND DISCUSSION

4.1 Introduction

This chapter comprises of four section to present and discuss the findings and results from both simulation and experiment. The first section will present and discuss the numerical results obtained from simulation, which included the stress distribution contour plot and clinched connection geometry parameters. The second section will show the experimental obtained clinched connection geometry parameters and discuss the effect of polymer on clinched connection geometry. The third section will compare and correlate the simulation and experiment findings, the geometry parameters and punch load versus stroke data will be compared. The last section will present the results obtained from single lap shear test and discuss the effect of joining force and material combination on joinability and failure modes.

4.2 Simulation result

Finite element analysis was performed on different hybrid material structure to study the effect of material combination on clinched connection geometry and stress distribution. Figure 4.1 – Figure 4.3 shows the stress distribution and final clinched connection geometry of different hybrid material structure. Besides that, punch load versus stroke data were also collected from the simulation, and it will be compared and correlated with experimental result and further discussed in section 4.4.

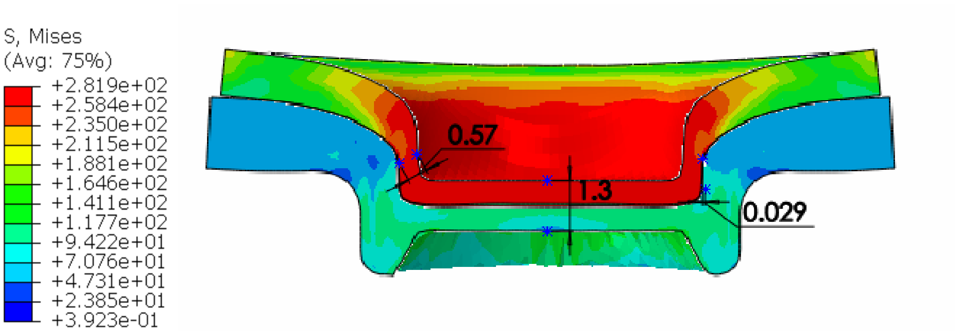


Figure 4.1 Stress distribution and final geometry of Al-PC clinched connection

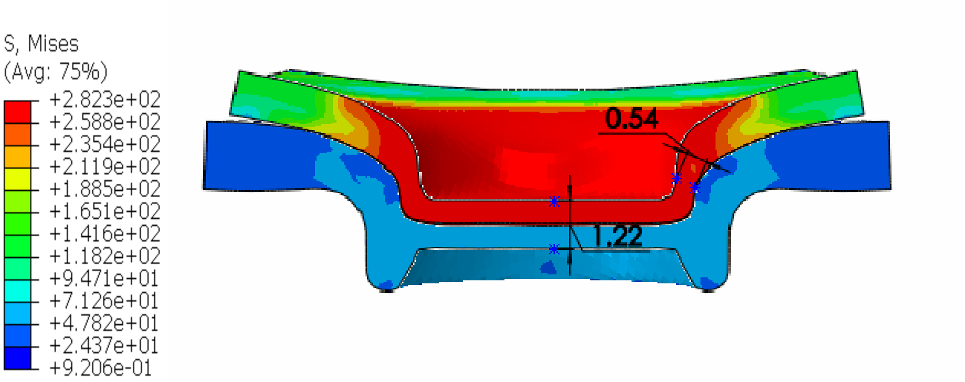


Figure 4.2 Stress Distribution and final geometry of Al-PVC clinched connection

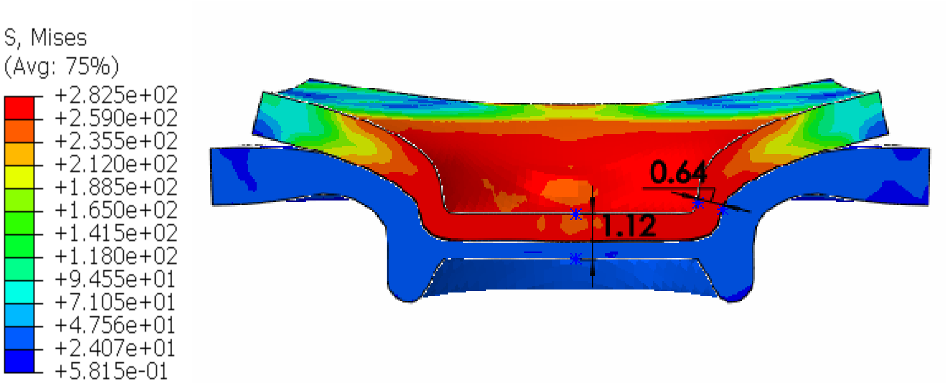


Figure 4.3 Stress distribution and final geometry of Al-HIPS clinched connection

The result shows that the type of polymers used for the formation of hybrid structure have minimal impact on the maximum stress level for the entire structure, but it affects the final geometry parameters which has great impact on the joinability and failure modes of the connection. Besides, it is evident that the upper sheet material which has direct contact with the punch is subjected to higher stress and deformation as compared to lower sheet, and thus during the clinching process, the tougher material that has higher yield strength must to be placed on top of the other material.

4.3 Experimental results

4.3.1 Punch load vs stroke

During the experiment, clinching was performed to join aluminium 5052 with polycarbonate, polyvinyl chloride and high impact polystyrene respectively. Figure 4.4 illustrates the setup of clinching process and illustrate the punching load direction. The punching load versus stroke data collected during the clinching process is presented graphically in Figure 4.5 and compared with simulation result in section 4.4.

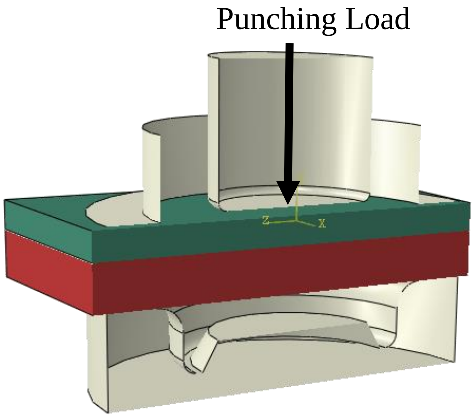


Figure 4.4 Illustration of clinching process

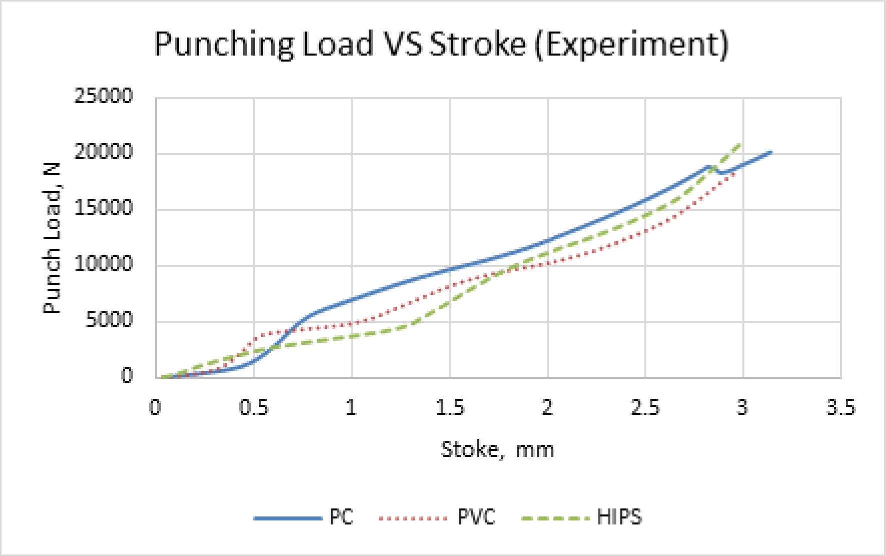


Figure 4.5 Punching Load VS Stroke

4.3.2 Clinched connections parameters

Geometry parameters of clinched connection such as neck thickness, interlock thickness and bottom thickness play a vital role in determining the shear strength and failure mechanisms of the clinched connections, and these parameters are greatly dependant on material combination. Figure 4.6 to figure 4.8 shows the cross-sectional view and geometry parameters of each hybrid material clinched structure produced by 20kN of punching load.

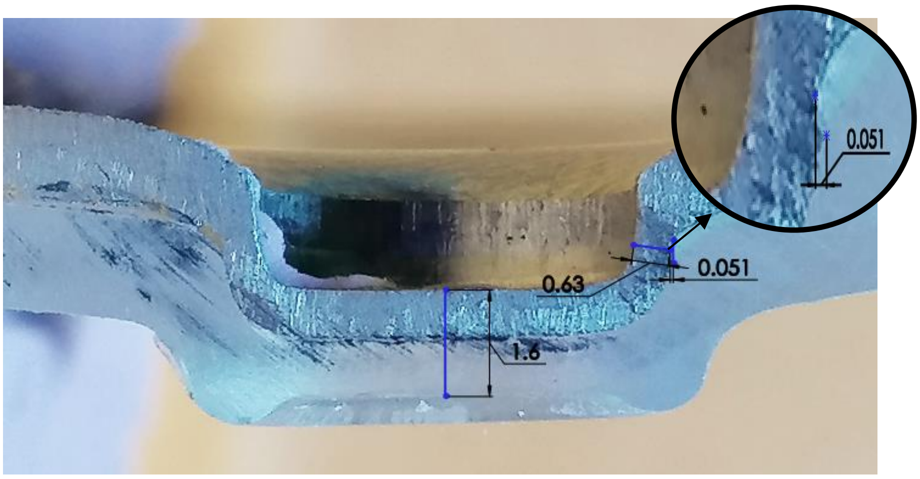


Figure 4.6 Cross-sectional view and parameters of Al-PC hybrid structure

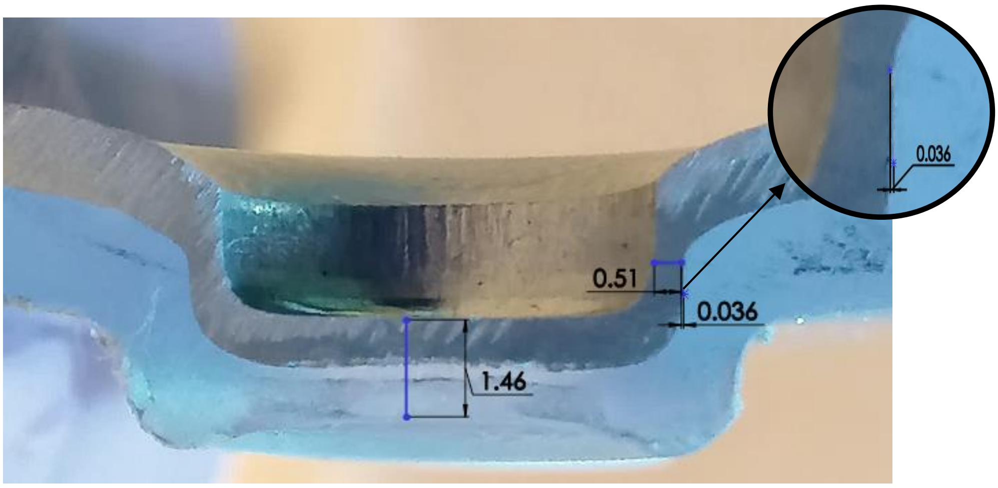


Figure 4.7 Cross-sectional view and parameters of Al-PVC hybrid structure

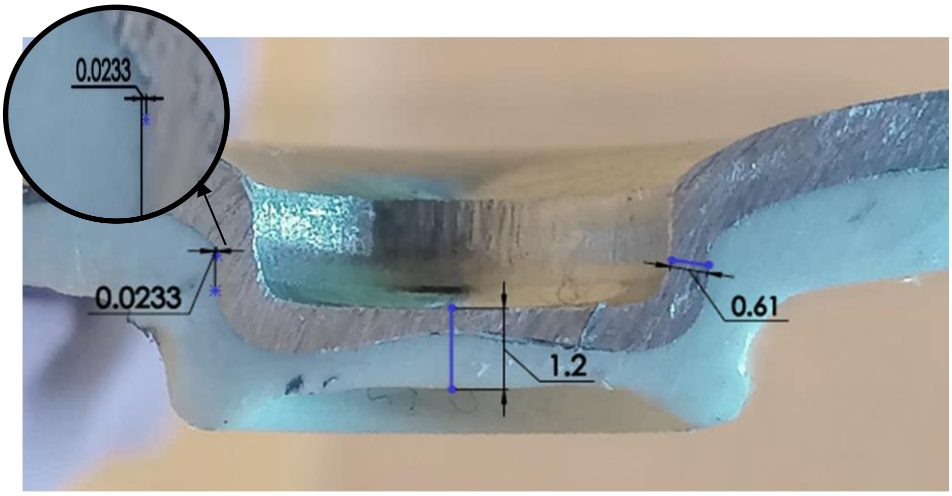


Figure 4.8 Cross-sectional view and parameters of Al-HIPS hybrid structure

The results suggest that clinch connection formed on hybrid structure with polymer with higher ductility and toughness such as polycarbonate will have relatively larger interlock and bottom thickness, on the other hand, hybrid structure formed with brittle and lower toughness polymer such as high impact polystyrene will have smaller interlock and minimum bottom thickness clinched connections.

4.4 Comparison between numerical simulation and experimental results

As mentioned in the earlier section, besides providing better understanding on how to simulate clinching by using finite element method, numerical simulation also served the purpose of validating experimental result. Thus, the clinching process simulation result is compared and corelated with experimental result in this section. Figure 4.9 compares the clinched connection's final geometry between simulated and experimental results.

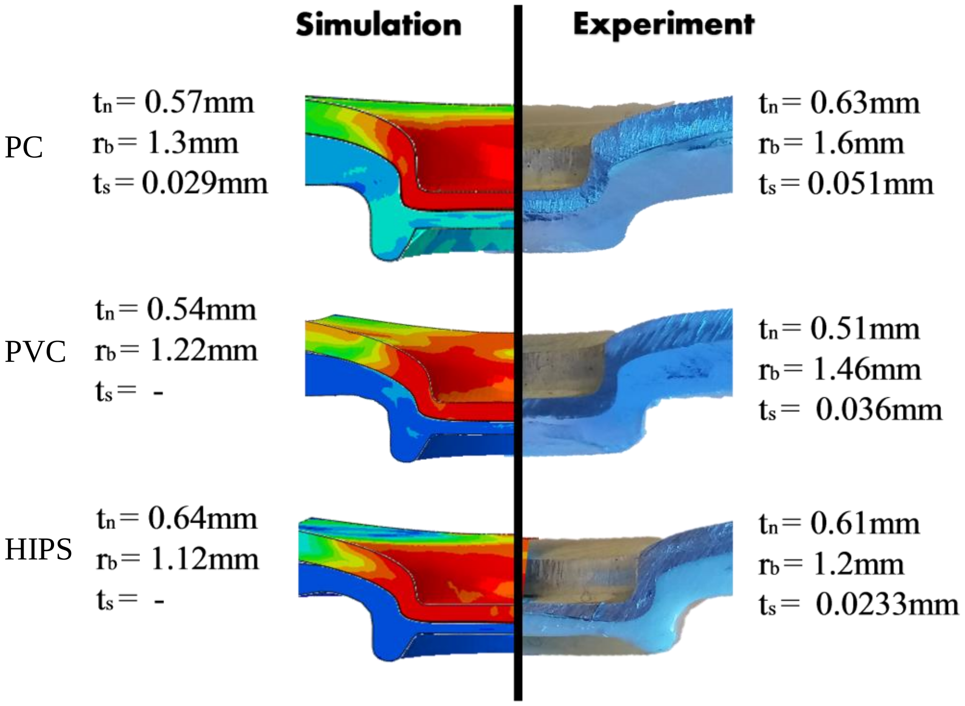


Figure 4.9 comparison of clinched connections geometry between simulation and experiment

As shown in Figure 4.9, the geometry parameters of both simulated and experimental results show great similarity except for the neck thickness, and this is because the interlock thickness of the hybrid structures were too small as compared to the mesh size used. By just reducing the mesh size, the problem will be rectified and the approach is good to be used for the purpose of predicting the final geometry parameters and in turn predicts the failure mode of the respective connection.

Besides that, the punching load versus stroke data for both simulation and experiment clinching process were also collected and compared in Figure 4.10 – Figure 4.12.

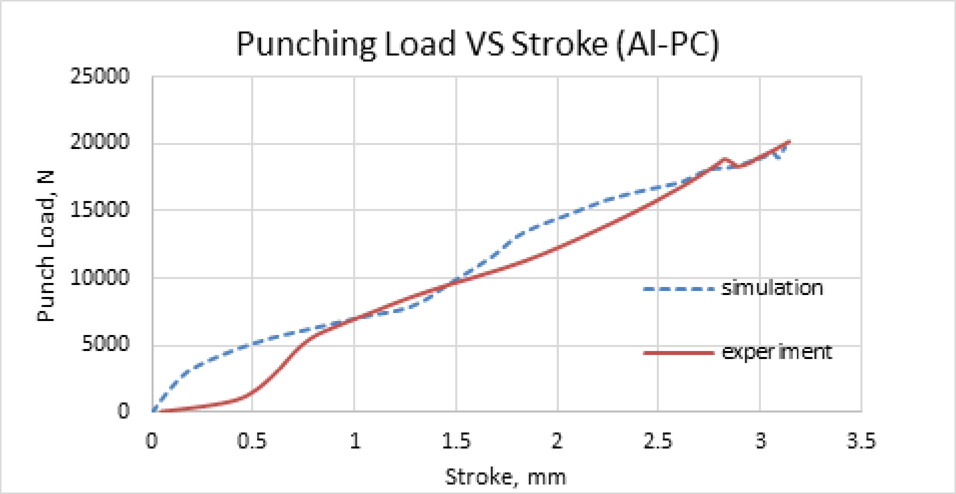


Figure 4.10 Punching Load versus Stroke for Al – PC clinch connection

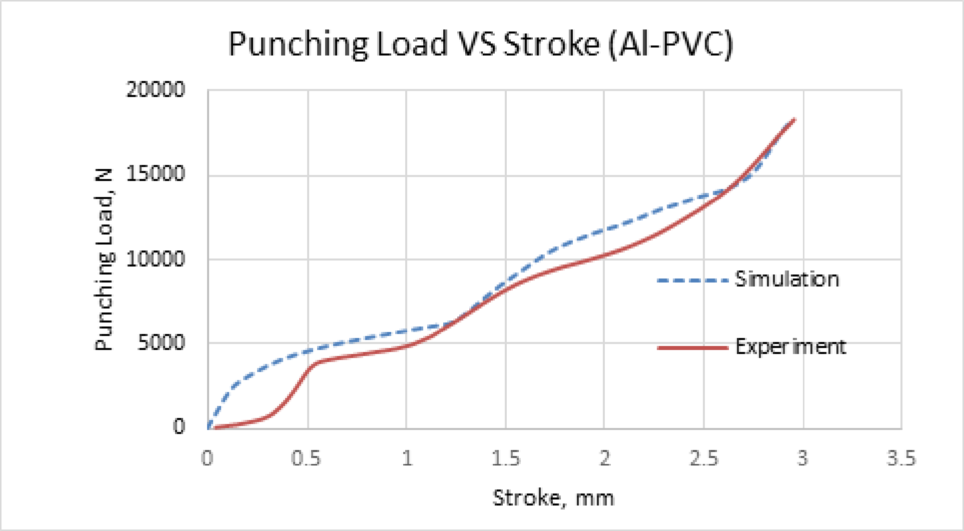


Figure 4.11 Punching Load versus Stroke for Al-PVC clinch connection

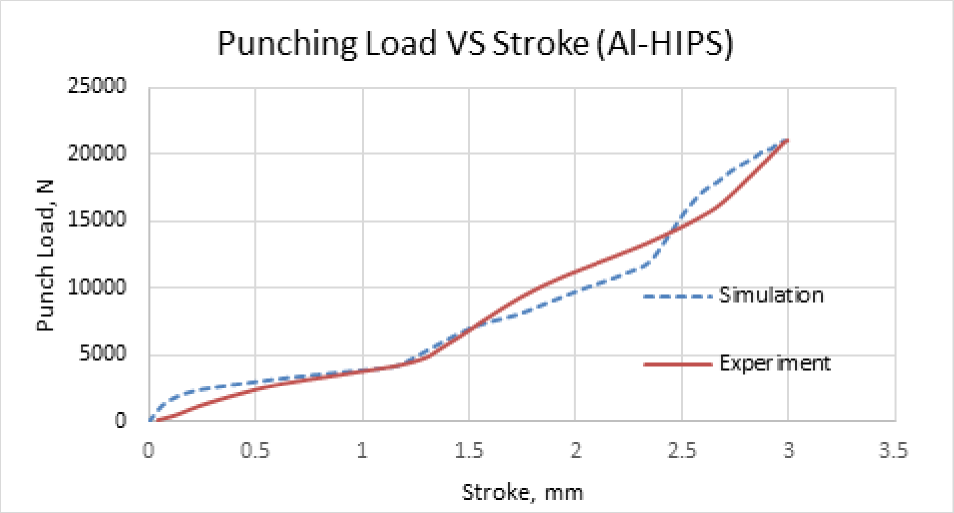


Figure 4.12 Punching Load versus Stroke of Al-Hips clinch connection

As it can be noticed, the punching load versus stroke results shows a strong experimental-numerical correlation and indicate a great overall agreement between each other. This implies that the approach used in the simulation for clinching process is valid, and thus the simulation approach used is suitable for the purpose of determine processing parameters, material combination selection and optimize joint strength in the future.

4.5 Single lap shear test and failure modes

4.5.1 Shear Strength VS Punch load

After the clinching process, shear strength of all the hybrid clinch connections formed at different punching load was assessed by means of single lap shear test. Figure 4.13 illustrates the single lap shear test conducted to assess shear strength.

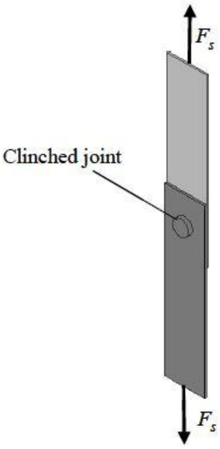


Figure 4.13 Illustration of single lap shear test

Different types of failures were observed during the test, for example, button separation, pull out, neck fracture and polymer fracture. Figure 4.14 to 4.16 show the relationship between punching load and hybrid connections' shear strength and also the corresponding failure mode.

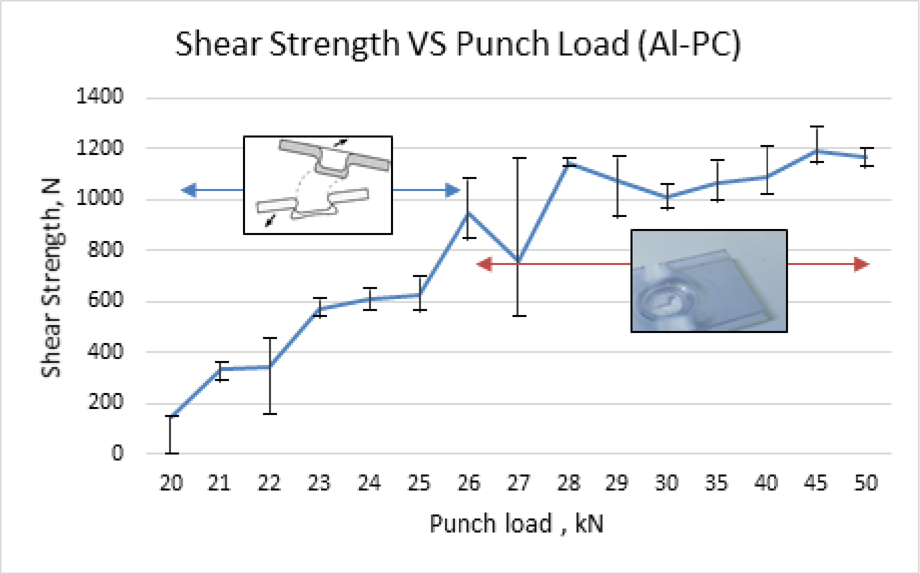


Figure 4.14 Shear Strength VS Punch Load (Al-PC)

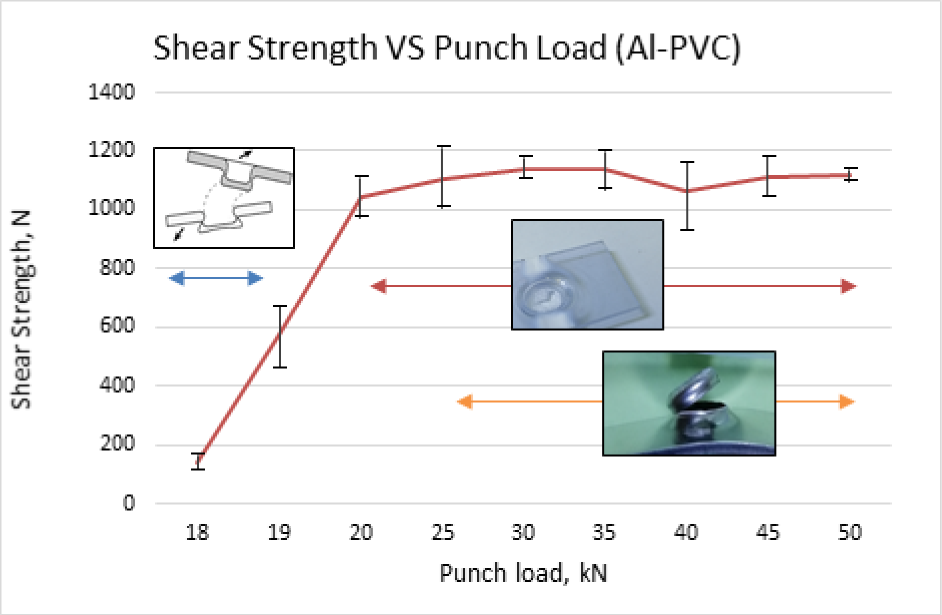


Figure 4.15 Shear Strength VS punch Load (Al-PVC)

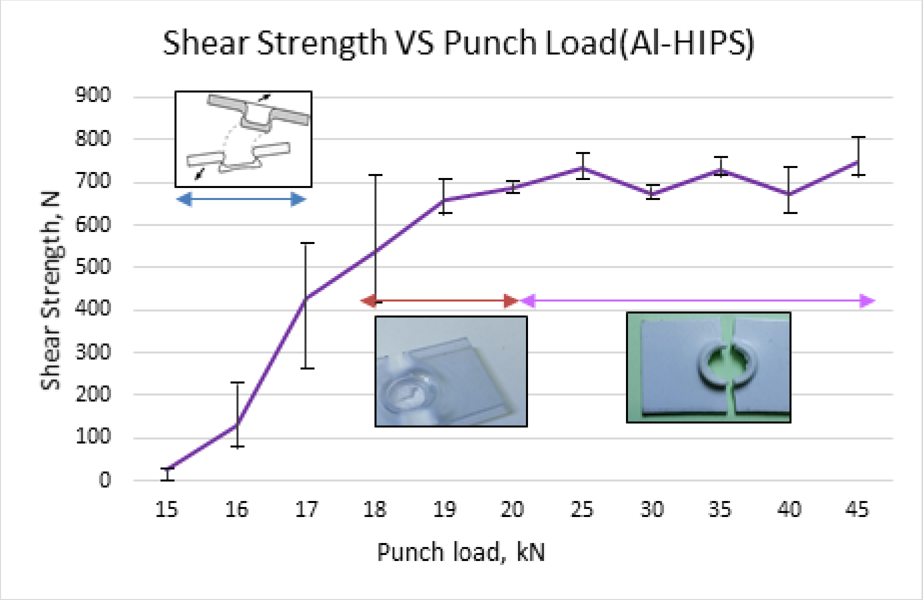


Figure 4.16 Shear Strength VS punch Load (Al-HIPS)

Based on the result as shown in figure 4.14, 4.15 & 4.16, it appears that round grooved clinch tool able to form sound hybrid clinch connection on PC, PVC and HIPS successfully with maximum joint strength up to 1.28kN, 1.21kN and 0.8kN respectively. Besides, it can also be noticed that the punching load has great impact on the joinability of the hybrid structure and the corresponding failure mode. The shear strength of the clinched connection which represent the joinability of the hybrid structure increased linearly with the punching load until the optimum point is achieved. Further increased of punching load after the optimum point does not increase the joint strength of clinched connections significantly. Table 4.1 summarizes and compares the optimum point shear strength and maximum shear strength.

Table 4.1 Comparison of optimum punch load shear strength and maximum shear strength.

Hybrid Structure		Al-PC	Al-PVC	Al-HIPS
Optimum	Shear strength, N	1130	1041	707
	Punch load, kN	28	20	25
Maximum strength	Shear Strength, N	1284	1211	805
	Punch load, kN	45	25	45

From Table 4.1, it can be deduced that, the maximum shear strength does not differ much from optimum shear strength, however the punch load required to produce maximum strength hybrid connections as much higher than the punch load required for optimum shear strength connection. Thus, it is advisable that clinched connections should be produced with optimum punch load instead of maximum shear strength required punch load.

4.5.2 Shear Force VS Displacement

Figure 4.17 shows the shear force versus displacement graph recorded during the single lap shear test of clinched connections formed on different hybrid structure.

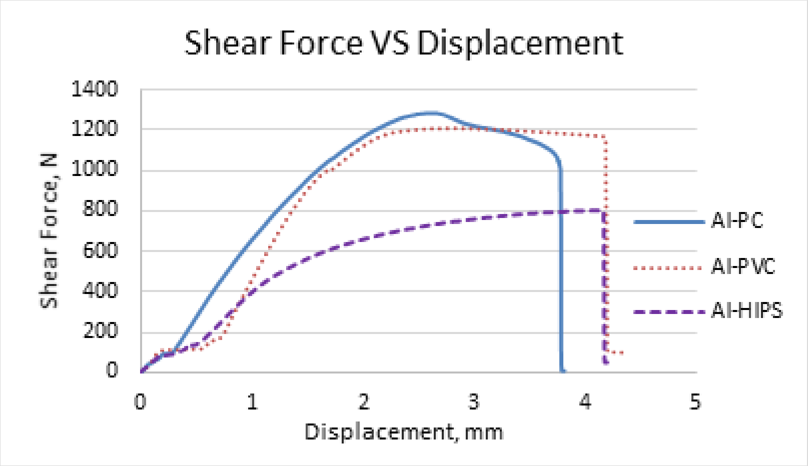


Figure 4.17 Shear Force versus Displacement

It is shown that the hybrid connection formed on polymers with higher yield strength such as PC and PVC are characterized by higher shear strength, while hybrid structure with lower yield strength polymer such as HIPS is characterized by lower shear strength.

Besides, based on the result, it can also be noticed that the trend of each hybrid connections is different. For Al-PC hybrid structure, the shear force reduces slowly after reaching the maximum shear force because of the prolonged effect of pull out, then the force drops steeply after the metal bulge is completely separated from polymer button. On the other hand, for the Al-PVC, due to the pull-out effect, the shear force also reduces slowly after reaching the maximum, but the neck fracture failure of the connection results a more sudden drop of shear force after the breaking strength of metal bulge is reached. For the Al-HIPS hybrid structure, the shear force drops directly after it reached the maximum shear force without giving any sign owing to the sudden fracture of brittle HIPS.

4.5.3 Failure modes

During the single lap shear test, four different types of failure mechanisms were observed, namely button separation, neck fracture, polymer fracture and pull-out.

Button separation is a typical failure mode occurs on clinched connections with insufficient interlock between two sheets. Based on Figure 4.14, 4.15 and 4.16, it is evident that button separation failure only occurs on clinch connection formed at low punching load. This is due to the reason that when the punching load is small, the material flow which produce the interlock will be minimum and thus the interlock formed is relatively small and resulting a clinched connection which unable to hold two material sheets together. Figure 4.18 illustrates the button separation failure mode.

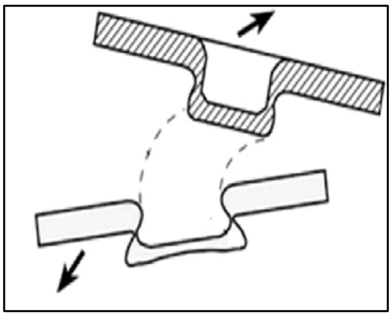


Figure 4.18 Button separation

As the punching force increases, the thickness of interlock increases. Clinched connections with adequate interlock and neck thickness formed on ductile polymers such as PC and PVC fails by pull-out. when the yield strength of the polymer is reached, the polymer button deforms and elongates plastically under the high pulling force of shear test. Then, the deformed polymer allows the metal bulge being pulled out from the button and separates the two sheets from the connection. Figure 4.19 a &b shows the picture of clinched connection failed by pull-out failure mode.

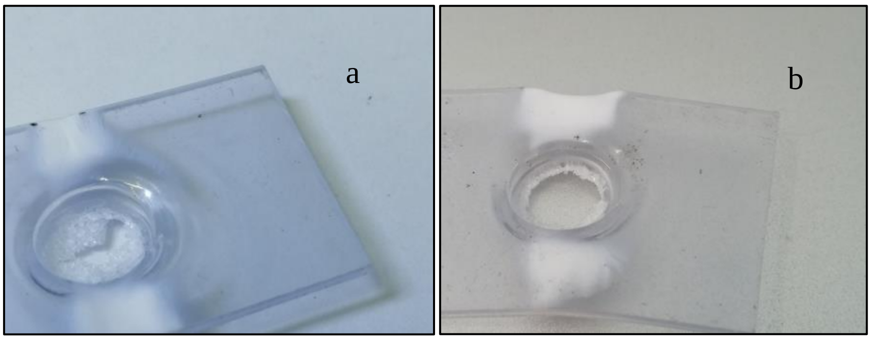


Figure 4.19 a & b pull-out failure mode

However, if such clinched connection is formed on brittle material with little or no strain hardening such as HIPS, the connection fails by polymer fracture, which is the brittle rupture of polymer sheet occurs perpendicular to the pulling direction. As depicted in Figure 4.17, connections with such failure tends to loss its load carrying suddenly without giving any sign. Thus, due its unpredictability, brittle material is not suitable for the use of high load carrying purpose. Figure 4.20 shows the polymer sheet of clinched connection failed by polymer fracture.

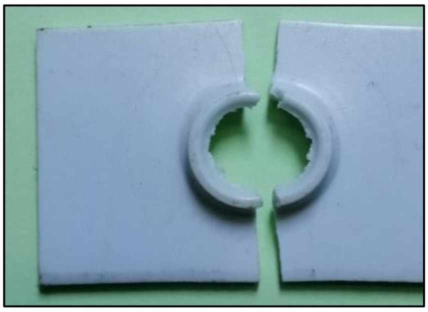


Figure 4.20 Connection failed by Polymer Fracture

The further increase of punching load, increase the size of interlock and reduces the metal bulge neck thickness. Clinched connections having relatively small neck thickness and large interlock fails by neck fracture, which is the fracture of metal bulge. As shown in Figure 4.21a neck fracture failure can be a partial fracture of metal bulge which followed by pull out of metal bulge or a total fracture of metal bulge as shown in Figure 4.21b.

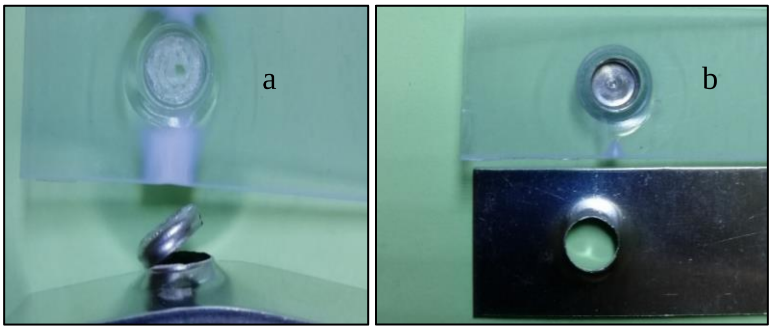


Figure 4.21 a & b partial neck fracture and total neck fracture

In short, based on Figure 4.17, it is evident that the neck fracture failure is more predictable than the polymer fracture as the load carrying capability of the connections drops gradually prior to the total loss of load carrying capability due to the prolonged thinning effect occurs on metal bulge. For this failure mode, preventive measures can be taken once gradual drop was observed and prevent the occurs of catastrophic failure of the structure.

4.5.4 Summary

It was found that round grooved clinch die is suitable for joining aluminum 5052 with polycarbonate, polyvinyl chloride and high impact polystyrene. It was also found that, joining force and material combination have great impact on joint strength and failure mode. With adequate punching force, the maximum joint strength of Al-PC, Al-PVC and Al-HIPS hybrid structure joint can go up to 1.28kN, 1.2kN and 0.8kN respectively.

In the single lap shear test, four different types of failure modes were observed, namely button separation, neck fracture, pull out and polymer fracture. Button separation occurred due to insufficient interlock which is the stem of insufficient punching load. Neck fracture occurred due to excessive punching load which tremendously reduced the neck thickness or induced crack on the metal bulge. Pull out occurred on clinched connection with adequate interlock and neck thickness, but the structure failed because of the large pulling load elongated and deformed the polymer button and force the bulge rotate out from the button. Lastly, neck fracture is a typical failure mode occurs on brittle material which fracture suddenly without plastic deformation.

Simulation result obtained were in agreement with the experimental result in the aspect of deformed connections geometry and punch load versus stroke curve. Both of the results have shown a strong experiment-numerical correlation. It is evident that the approach used in simulation and method used in experiment is valid and suitable for further study of clinching process in the future.

CHAPTER 5

CONCLUSION AND RECOMMENDATIONS

5.1 Conclusions

This study has investigated the feasibility of forming Aluminium 5052 – polymers hybrid clinch connections by using round grooved clinch tool set. It was found that round grooved clinch die is able to produce sound clinched connection between Aluminium 5052 and polymers such as polycarbonate, polyvinyl chloride and high impact polystyrene and the maximum shear strength of the hybrid clinched connections formed are 1.28kN, 1.21kN and 0.8kN respectively. This finding provides clear evidence that round grooved clinched die is feasible to be used to create hybrid clinch connection between metal and polymer. It is also found that the punching load has great impact on the joinability and failure modes of the hybrid structure, inadequate punch load will cause insufficient interlock, while too much punch load does not increase the joint strength significantly. Besides, the behaviour and failure modes of clinched connections is in agreement with (Lambiase, 2015a) study, which stated that failure mode of the clinched connections is highly depended on polymer toughness, tough polymer hybrid connections failed by neck fracture or button separation while brittle material failed by polymer fracture. On the other hand, finite element analysis was also carried out to validate the experimental results, and the results have shown a strong simulation-numerical correlation. This implies that the approaches used in the finite element analysis is valid and it is suitable to be used to optimize joint strength and predict failure in the future work.

5.2 Recommendations for future work

In this study, different types of polymer were used to form hybrid clinch connections, but only one type of metal was used in the study, which is Aluminium 5052. The joinability of other metals have not been explored in this study. Future study should attempt to use different type of metal to form hybrid connection with polymers.

Besides, due to the limitation on machine availability, polymers tensile specimen used for material characterization process was produced by laser cutting or CNC milling instead of the ASTM standard specified methods: ejection molding and compression molding. To further improve the accuracy of future research, polymer tensile specimen should be fabricated by following ASTM specified methods.

Apart from that, as the mesh size is a trade off between accuracy and computing time, by considering the computing time and power it might cause, the mesh size used in the simulation was 0.2. If time and computing power is allowed, future study should attempt to use smaller mesh size to improve the accuracy of the result.

lastly, on account of its material properties superiority, carbon fibre reinforced polymer is gaining its popularity in many industries for light weight purpose. However, joining of carbon fibre reinforced polymers with metal is also very challenging as they cannot be simply joined together by traditional joining method such as welding. Thus, the joinability of metal with carbon fibre reinforced polymer should also be studied as an extension of this research.

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